COMPUTERIZED FORECAST OF LATERITE-BAUXITES OF PLATEAU AND PENEPLAIN TYPE

A complex computer-enhanced forecast method for preliminary assessment of the ore grade and resources of laterite-bauxites that may be expected to occur on prospective plateaus and peneplains

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INVESTIGATIONS IN FOREIGN COUNTRIES: METHODS AND APPLICATIONS

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A GLOBAL AND REGIONAL REVIEW

1. AN OUTLINE OF THE AGGREGATE BAUXITE RESOURCES OF THE WORLD

In terms of the surveys and estimates prepared in the early 1980's the Earth's bauxite resources are estimated (V. G. HILL–S. OSTOJIĆ, 1981) to amount to about 140 thousand million MT, of which about 9 thousand million MT are karstic bauxites. The commercial bauxite reserves in a more strict sense (bauxites suitable for industrial use) are much less than that figure. As estimated most recently by GY. BÁRDOSSY (1987), the Earth's bauxite reserves are about 54.0 thousand million MT, of which 47.5 thousand million MT are lateritic bauxites, 6.2 thousand million MT karstic bauxites and 0.3 thousand million MT bauxites of the so-called Tyhvin type. LOTZE's estimate (1978) in the same classification gives 32 thousand million MT of lateritic bauxite and 6.7 thousand million MT of karstic bauxite. According to the survey carried out by E. SZABÓ in 1987, the Earth's probable bauxite resources amount to 60.5 thousand million MT, of which 54.1 thousand million MT are lateritic bauxites, 6 thousand million MT are karstic bauxites and 0.4 thousand million MT are bauxites of Tyhvin type. As evident from the above list of estimates made with a time span of ten years, there is a rather wide scatter in the figures listed. In fact, there are estimates suggesting even greater extreme values. So, for example, TENYAKOV places at about 200 thousand million MT the upper limit of the potential bauxite resources. For a comparison according to authors, the major individual reserve estimates are given in Fig. 1.

The Earth's bauxite resources are dominated, undoubtedly by the lateritic bauxites with an estimated 25–186 thousand million MT of resources, the lateritic versus karstic bauxites ratio varying between 5:1 and 16:1.

The quantitative differences in the resource estimates are basically due to the very high degree of uncertainty primarily in the case of the lateritic bauxite resources, for these, though most of them occur scarcely buried, almost completely exposed on plateaus (about 80%), are, in some allegedly prospective regions (mainly the intertropical areas of the developing countries) still fully unknown or, for that matter, merely surmised. On account of this, the conclusion may be drawn that the lateritic bauxites of the Earth and primarily the lateritic bauxites of plateau type are that which may turn out to have a surprise in store as far as the real assessment of the reserves is concerned. The standard deviation in this case may account for about 60–70% of the currently estimated maximum of the global bauxite resources.

Not until the decades that followed the Second World War did a real upswing in the complex scientific research and mineral exploration aimed at eliminating the uncertainty

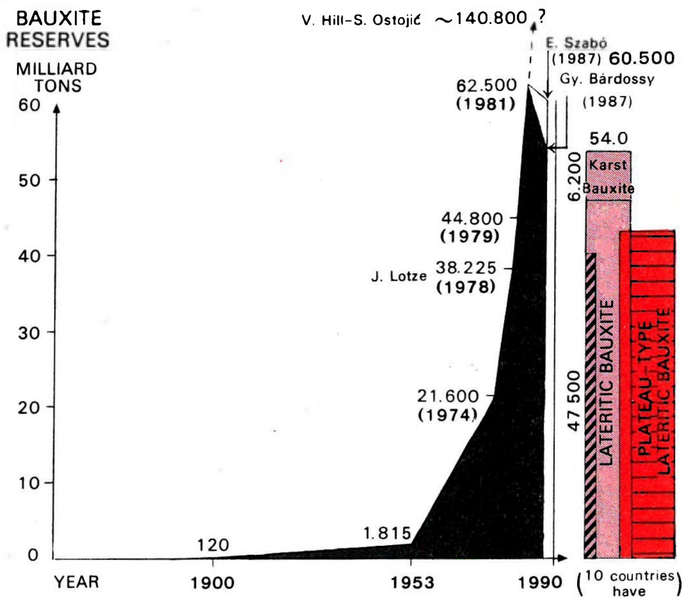

Fig. 1 Development in global bauxite reserves
(Prospected and potential reserves of the world)

factor take place. That was the time when large lateritic bauxite discoveries were made on various continents within the intertropical zone. To quote just a few examples: Weipa and Gove, Darling Range and Mitchell plateau (Australia), Rio Trombetas, Oriximina, Almeirium, Paragominas in the Amazon basin (Brazil), Orissa and Andhra Pradesh plateaus (India) or, to list the latest discoveries in the 1970's: Los Pijiguaos (Vezeuela), Mnong, Baoloc, Pleiku, etc (South Vietnam).

The major discoveries and the progress in exploration were coupled with complex, interdisciplinary investigations (geo- and plateau-morphological, petrographical and mineralogical, microclimatological, water balance studies, etc) (ZANONE 1971, VALETON 1972, GRUBB 1973, GIDIGASU 1976, MCFARLANE 1976, BÁRDOSSY 1981, ALEVA 1983–84, VÖRÖS–MINDSZENTY 1973, H. SZILÁGYI 1980, BALKAY 1971, SEGALEN 1971, MIKHAILOV 1969, GERASIMOV, KRAUSKOPF, SAPOSHNIKOV, SZABÓ 1981, 1982, 1983, BOULANGÉ 1984 and many others).

It was not by chance that the international forum for studying the very wide range of topics embracing the problems of laterites and lateritic bauxites selected India to hold its statutory meeting in–a country, where the classic "laterite" had been described, in 1821, by BUCHANAN and where, in 1976, the joint-venture UNESCO–IGCP Project No. 129 convened the best professionals and the most prominent contributors to the topic to form working groups at and chair the sessions devoted to "Lateritisation Processes" (P. K. BANERJI, V. VENKATESH, G. J. J. ALEVA, J. J. TRESCASES, D. SAPOSHNIKOV, A. MELFI, C. R. M. BUTT, GY. BÁRDOSSY, S. S. AUGUSTITHIS, J. J. LA BRECQUE, W. SCHELLMANN, H. R. POLLACK, Y. OGURA).

During the very short time of its existence, "Project No. 129" led to the solution of a good many of scientific and practical problems, concentrating the efforts, quite correctly, to discussing important questions and finding solution to them. Its periodical bulletin, the "Newsletter" of which 5 issues have appeared thus far, published papers or reports written by many well-known experts of laterites and lateritic bauxites and it launched discussions on relevant scientific problems. In 1986, the final report on Project activites was issued in a separate volume.

In 1963, in Zagreb, Yugoslavia, a very important international scientific organization, the International Committee for the Study of Bauxite, Alumina and Aluminium (ICSOBA), was formed. During the quarter of a century that has elapsed since its founding, ICSOBA has largely contributed to the study of lateritic bauxites. In spite of these developments, a summarizing account of the assessment of the lateritic bauxites of the Earth in general and of the plateau-type lateritic bauxites in particular, based on a realistic and all-round survey, or a method enabling fellow professionals to eliminate the uncertainty already referred to is still badly missed*.

An exhaustive elaboration of the afore-mentioned topic requires the solution of rather complex and intricate problems. Thus, it seemed to be advisable to develop a new classification of lateritic-bauxitic plateaus prior to proceeding to the synthesis. Some of the authors (GY. BÁRDOSSY, E. SZABÓ) have recently been increasingly concerned with the question of geological and/or economic evaluation of plateau-type lateritic bauxites and laterite-bauxite plateaus and, in this context, with finding out the characteristics and mathematical relationships enabling their computerized processing with a view to developing a forecast system for the assessment of the Earth's bauxite deposits of this type, too.

Since about 90% of the lateritic bauxite plateaus is mainly in developing countries, in the intertropical zone, the forecast method here proposed, when adopted, will give an impetus to a more realistic assessment of the mineral resources potential of developing countries that are supposed to have a wealth of bauxite resources on the plateaus and thus provide a more solid base for the planning and development of selected branches of their national economies. On top of that, the method which gives the prospective bauxite resources (quantitative and qualitative estimates) and their geopraphic distribution at a probability level that is higher than has heretofore been the case, may result in considerable exploration cost savings as well.

And now let us get familiar with the basic principles that are important for the forecast and with the new forecast method adapted to computerized data processing.

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* An overall scientific book written by ALEVA and BÁRDOSSY was put under press when this booklet was being compiled.

2. FUNDAMENTAL CRITERIA

In the light of present-day knowledge, the formation and preservation of plateau-type lateritic bauxites and their quantitative and qualitative characteristics are controlled by each of the following principal factors separately and by their natural interactions:

2.1. *Source rock*

2.1.1. Chemical composition.

2.1.2. Mineralogical composition.

2.1.3. Petrophysical characteristics.

2.2. *Climatic factors* (regional and microclimate in the geological past up to recent time).

2.2.1. Precipitation (distribution, annual average, seasonal distribution, periodicity, runoff, infiltration, evaporation, relative moisture, indirectly Eh-pH conditions).

2.2.2. Temperature (annual average and fluctuation, seasonal average, absolute, maximum, minimum, daily fluctuation, dew point, relative moisture, annual, seasonal and daily variation, etc).

2.3. *Biological factors* (vegetation: marsh, pond, rain forest confined deciduous forest, savannah with sparse woods, shrubby-grassy savannah, semi-desert), marker plants (fauna: burrowing beetles, termites, ants, etc).
Slope-stabilizing role of vegetation.

2.4. *Morphological factors*

2.4.1. Morphology of slopes (gentle slopes, steep slopes, scarps, inflections, varying and steady slopes, incisions, steep convex slopes with bauxite (30° or even 45°, e.g. Poços de Caldas, Serra de Mantiqueira).

2.4.2. Plateau morphology (level, flat, dissected, concave, convex, undulated steadily sloping, dissected tongues, necks, ridges, crests, types of drainage such as multichannelled, with swamps or without them, intermittent or permanent, importance of the "drainage pattern", sites of tapping the high, moderate and deep groundwater table, sites of gullying of springs, etc).

5. ORGANIZATION, WORKING PHASES AND STEPS OF IMPLEMENTATION OF THE NEW FORECAST METHOD. AN INTERNATIONAL COORDINATION CENTRE, ITS ORGANIZATIONAL PROBLEMS AND ROLE

For the assessment of the mineral resources potential of a considerable part of the Earth, a project to be carried out according to uniform principles with involvement of at least 30 developing countries as required by the magnitude of the task, an *international coordination centre* and *national working groups* will have to be organized.

The organization is proposed to be set up in the specialized branch of the *United Nations Organization*, the UNIDO (with headquarters in Budapest or possibly in Vienna), while the national working groups ought to be affiliated to ICSOBA or to be organized under the auspices of UNESCO–IGCP Project No. 129 or as a sub-project to be launched as its continuation. The date proposed for starting the whole survey is 1 January 1989, the date of its completion being not later than 31 December 1993. The whole computerized processing will take a maximum of 5 years time. Recommended to be titled "New Computerized Forecast of Plateau-Type Laterite-Bauxites", the project should be referred to in an abridged form as "PLB-(Sub)-Project" (Plateau-Laterite-Bauxite Project).

The *International Coordination Centre* will have as its duty to coordinate the Project needs by countries, to provide the experts needed for launching the work and contract their employment for a definite length of time. It will have to exert occasional supervision of the national working groups so as to check the observation of their engagements stipulated in contract. Further duties include administration functions, dealing with financial matters and procuring funds (contributions from the UNO, the UNIDO etc).

Annual average of cost required for running the Project efficiently (specialists + equipment, computerized processing operations, reconnaissance helicopter flights, sampling, field-work, etc).

The annual average of personnel may vary from 50 to 100 persons. This figure includes the staff (about 30 persons) of the International Coordination Centre as well.

Recommended composition of the International Coordination Centre:

1 president

2 vice-presidents

responsibles for five continents to be represented by both head-executives and experts

10 administrators (2 administrators for each continent)

5 typists

1 head-executive of computer crew

1 applied mathematician

3 operators

1 additional helping hand (to operate telephone and telex)

In addition, national working groups with a staff of 5 to 15 persons each (1 contact-person per country from about 10–15 countries).

The organization ought to be carried out in 1988. The mandates of the Project employees to be enacted upon nomination and appointment under the auspices of UNO, UNESCO–UNIDO or ICSOBA ought to be contracted for concrete lengths of time (1–2 or 5 years) or for concrete targets.

The concrete working phases of teams working in the individual countries will in general include (the project being impossible to implement, unless the work is done in several steps):

Collecting of basic data and documentation

1. *Basic data concerning laterites and laterite-bauxites*, the totality of earlier-discovered traces or data of laterite/laterite-bauxite (sample and analytical results, location, date of sampling, name of sampler, etc) are to be assembled, checked for reliability, and indicated on the map. Procure and stipulate rentability conditions for bauxite mining as adapted to the circumstances of the country involved.
2. *Collect climatological data* (at large and microclimate) (data, map-sketches, charts, measuring stations, etc).
3. *Collect geological data* (geological maps with the formations on and profiles on scales of 1:250 000, 1:200 000, 1:100 000, 1:50 000, 1:25 000 and 1:10 000, samples with chemical analyses, etc).
4. *Collect aerial photographs, satellite imagery*, interpreted and converted results, air-surveyed maps, etc.
5. *Collect reliable topographic maps* of selected areas including the most detailed map-sheets on scales of 1:250 000, 1:200 000, 1:100 000, 1:50 000, 1:25 000 and 1:10 000. In case of necessity and occasionally, even more detailed cartographic material may be collected, if obtainable.

Delineation and location of prospective areas

6. Delineate *prospective areas*, by a *discard-and-select approach* in several steps by relying on a special system of criteria.
   - 6.1. Climatic control I (at large)
   - 6.2. Climatic control II (microclimate)
   - 6.3. Geological (source rock) control
   - 6.4. Geomorphological control in general
   - 6.5. Plateau morphological control in particular
     - 6.5.1. Plateau
     - 6.5.2. Slope conditions (hillsides)
   - 6.6. Aerial photographic control
   - 6.7. Control by detailed helicopter traverses (where needed and possible)
   - 6.8. Biological control (vegetation and, possibly, fauna)
   - 6.9. "Drainage pattern" control (phreatic groundwater table)
   - 6.10. Tectonic and surface erosion control
   - 6.11. Final environment-related, recycling control of most promising areas
   - 6.12. Study of environmental protection circumstances and infrastructure

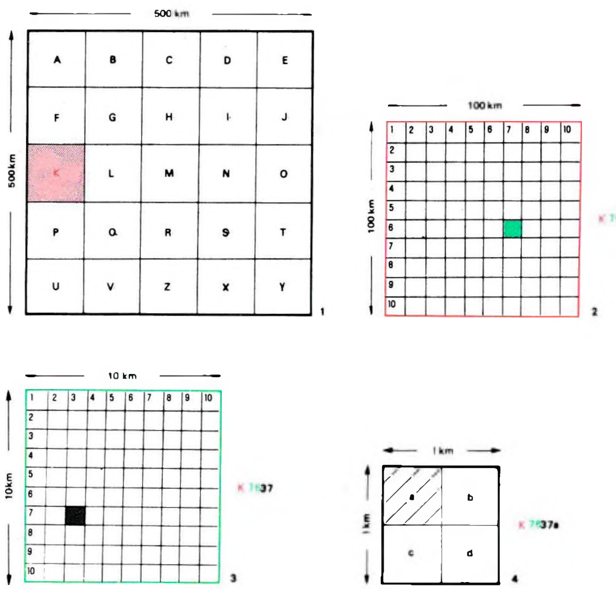

Fig. 2 System of symbols (letter- and numerical symbols) for the (prospective) areas recommended for inclusion in the survey (E. SZABÓ 1987).

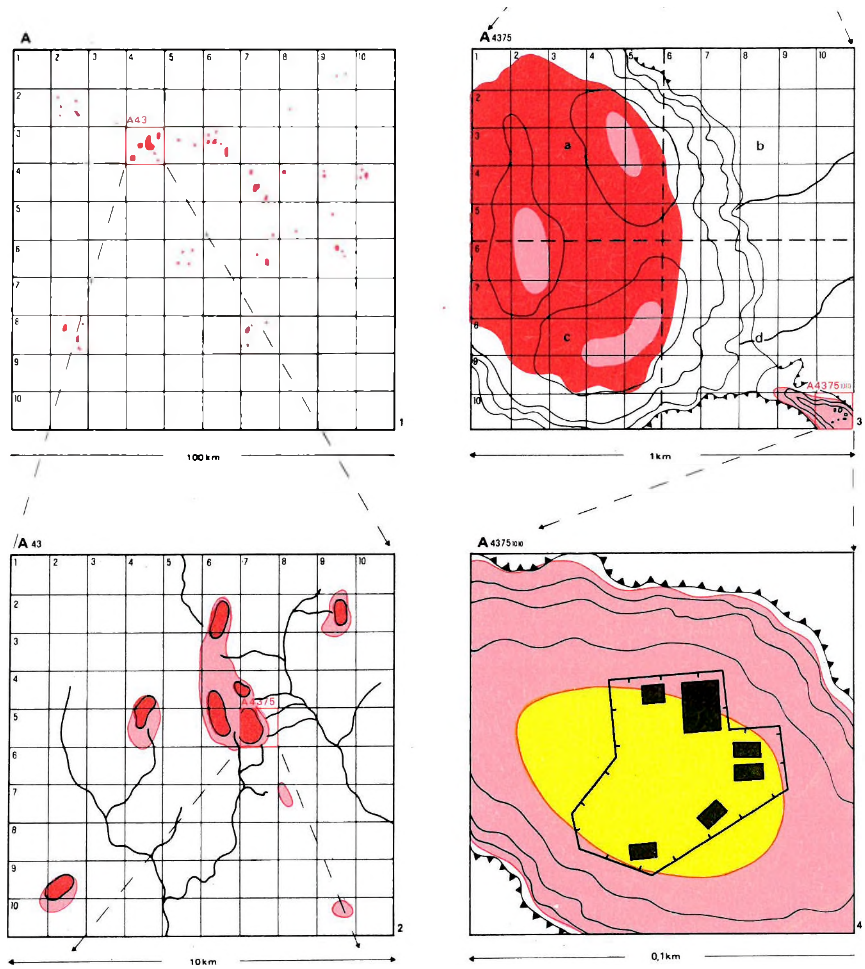

Fig. 3 Idealized sketch-maps in the square grid system

Preparation for and processing by the computer

7.* *Measure*, calculate, convert, evaluate and register *characteristic key data* (use of know-how) (expert work). Prepare data for being fed into computer.
8.* *Register key data on data-sheets* for the purpose of computerized processing (direct input system).
9. *Computerized data processing by areas and by bauxite deposits* (1, 10, 100 km^2) (occurrences). Interpret the data in form of text, in order to have a national summarizing account and evaluation in writing.
10. Work out summarizing data sheets for the particular country (observing uniformized principles) and send them to the Data Bank of the International Centre (in Budapest or Vienna). Safeguard the secrecy of confidential data. Prevent access of unauthorized persons to them. (The use of a special code system to this end is conceivable.)

Phases of work to be done by the International Centre alone:

1. Preparation for computerized processing of the summarizing forecast data sheets sent in by *the international working groups* (their recoding according to uniformized principles).
2. Computer-enhanced preparation from the recoded national summarizing data sheets of a *"Global Aggregate File"* on completion of the Project, in 1992.
3. Publication in book form of a *summarizing account* (a synthesis in form of text and tabulations). The material of each country is to be forwarded to the particular country for distribution among the users (business companies, firms, institutions, scientific academies, competent ministries, governments) before 1995.

The cost involved will have to be borne by UNO's UNESCO–UNIDO organizations and/or, in case of consent, by the individual countries.

* Further details of the asterisked paragraphs 7 and 8 are available to interested clients only, as they are to be handled as "know-how" provided that special provisions have been made in contract! This material comprises a system of specifically coded data sheets.

6. REVIEW OF COUNTRIES WITH POTENTIAL LATERITE-BAUXITE RESERVES IN THE LIGHT OF THE NEW FORECAST METHOD

The modelling of plateau-type laterite-bauxitization, i.e. of lateritization as a multifactor process, is a complex task. As is usual in dealing with geological processes at large, to find out correlations between subfactors, to identify them and to formulate them mathematically, expressing them in numerical terms, is difficult to achieve owing to their not being understood in a detail and exactness that might make it possible to feed them easily into computer. This is true, however, only as long as you want to model the subfactors in accordance with the reality. If you wish to carry out the modelling with a simplification which is still acceptable for practical bauxite forecast, you must not go as far as "exaggerate the refinement" of the topic to be dealt with, but at the same time you have to avoid the error that may result from your tackling it too "broadly".

Let us emphasize therefore that when the authors are "modelling" with the new method here recommended for determination of the bauxite potential of only such laterite plateaus the morphology of which is well-known, they never mean to model the interaction of intricate processes taking place with varying intensity during hundreds of thousands or even millions of years in Nature, but they always understand under modelling a so-called sketch-modelling based on a more simplified approach to assessing the principal characteristics that are mere reflections of the subfactors involved. You must always bear in mind that the parameters serving the formulation of the characteristics are always measured in their present state and these data are valid primarily in the present cross-section of time, though they reflect the results of processes that set in and took place in the past and that are still going on at present.

Not even a "sketch-modelling" to be done as a kind of approximation can be achieved, unless a wide spectre of comparative studies and analyses has been performed. Such an approach is advisable to carry out for each particular country—for explored plateau-type deposits or for ones that are partly characterizable already by average data—, in order to determine factors that are really interrelated (correlatable) and distinguish them from factors that are not correlatable.

Inferred partly from the results of searches for tropical laterite-bauxites and from the author's own observations on the field, partly from talks and exchange of experience with some foreign and Hungarian specialists dealing with laterite-bauxites and partly from consultation of the wide spectrum of publications devoted to the topic, the more than 40 different correlation diagrams have encompassed the ample gamme of approaches aimed at finding out relationships that are important for forecasts.

Because of the variation of the interrelated factors within each particular country, in fact, sometimes even within single deposits and of the varying degree of their involvement, no mathematical formulas of universal validity to base the modelling on can be established. Regardless of the anomalies (extreme deviations in the positive or negative sense), some trends deduceable from the various relationships are obvious. Inferred from the data of a proper number of samples, the trends observable in correlation diagrams for a given area (e.g. country, or possibly a bauxite deposit) can be mathematically formulated. Moreover, conversion coefficients, factor-equivalents, can be developed from them. These coefficients can be extrapolated, by relying on analogies, to that (or those) environment(s) characterizable by physical parameters to which in the light of the parameter(s) of the plateau(s) under consideration (= climate, altitude a.s.l., source rock and its chemical composition, roughness of topography, water balance, as most important characteristics) they happen to be assignable. This means, in other words, that the use of the analogy method will enable the explorer to determine the unknown "model-pairs" of such bauxitic-lateritic plateaus having similar parameters as have proved to be productive: counterparts in which, regardless of the anomalies (as a rule not exceeding 30%), the occurrence of bauxites of similar genesis, type, character and grade in the "laterite-cap" or the rock sequence may be expected, just like that which is suggested by the position they occupy in the trends of the known plateaus.

The sequence of the analyses, as expounded in the preceding chapters, is a very important logical succession of processes such as the correlation–analysis–evaluation leading to the concrete resource calculation (quality and quantity) phase of the laterite-bauxite forecast.

To review and outline the geographic location and position of the laterite-bauxite plateaus or laterite-bauxite platform (+ extra-shield, so-called paraplatform) or peneplain areas of each country is aimed at by the series of map-sketches (charts) assembled and worked out in this chapter (Fig. 5–59).

What has been sought to achieve is to illustrate the possibilities and expected volume of the proposed survey by relying on comparatively freshest information. The pieces of information thus obtained include primarily the relevant literature data available or procurable as well as oral or written or graphic information received from individual experts and, in smaller measure, the results of the author's own observations and experience.

Extremely valuable contributions have been provided by talks and exchanges of experience the author has had the opportunity to have in recent years with a number of foreign or Hungarian specialists about questions of detail pertaining to the topic.*

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* Of these let us point out Mr G. J. J. ALEVA's oral communication and his papers concerning the laterites and bauxites of Suriname, Mr J. P. LAJOINIE's concerning those of Guinea, Mr M. RAO's, Mr K. S. SUBRAMANIAN's and Mr K. P. GHOSH's on those of India, Mr ARANHA P. ANDRADÉ's on those of Trombetas (Brazil), Mr H. R. POLLACK's on those of Bakhuys, Nassau and Lely Mts, Suriname and Mr ONG WE SACK's on those of Johore (Malaysia). From among the Hungarian specialists valuable data information and advice were contributed by GY. BÁRDOSSY, the late B. BALKAY, I. VÖRÖS, F. SZANTNER, Miss A. MINDSZENTY, GY. KOMLÓSSY, Mrs E. PERLAKI, GY. VARJU, S. VÉGH, Miss A. VÉGH, P. GORDOS, E. DUDICH, E. NAGY, GY. VECSERNYÉS and L. KORPÁS whom the author had consulted about the laterites and/or bauxites of Brazil, Madagascar, India, Pakistan, Nigeria Mexico, Ghana Burkina Faso, Zambia, Guinea Bissau and Cuba.

The Hungarian specialists paid visits of varying duration to one or more laterite-bauxite areas in order to study them bauxite geologically, geologically, to provide professional consultant's services, to assess the local situation, to conclude business contracts, to prepare case history studies, etc. In doing so, they acquired personal experience about the areas they had visited and studied. The information provided by the consultations (both in Hungary and abroad) has been incorporated into the map-sketches of the particular countries.

The main principle in compiling the sketch-map of each country has been to provide a relatively detailed sketch-map primarily of those countries in which the potential and identified bauxite resources combined are expected to exceed or at least to attain the figure of 100 million MT. An exception to the rule may be represented only by Salvador, Panama, Fiji, Tasmania, New South Wales, New Zealand and Burkina Faso, for the total identified and potential resources of none of these countries attain that limit.

At the same time "other countries that may be reckoned with" include–with no particular stress on though–nations which may have a resources potential magnitude as high as one thousand million MT, e.g. Cambodia, Laos, Zaire, or countries with a magnitude of 100 or 10 million MT, e.g. Nigeria, Zimbabwe, Republic of South Africa, Mozambique and Angola. Consequently, because of the total lack of data or the unreliability of the information available on various countries the contradictory assignations of the particular countries to this or that category, seemingly obvious as they are up to this moment, really exist on the outset–a fact the author is well aware of. To eliminate the contradictions is a task to carry out in the near future parallel to progress in the surveys and reasearch that are supposed to be launched.

Data on traces, resource indications and deposits of bauxites are available from a host of countries (e.g. Paraguay, Bolivia, Argentina, Chile, Chad, Togo, Congo, Liberia, Zambia, Tanzania, Kenya, Seychelles Islands, Papua, Burma, Taiwan and several islands from the Pacific), but their reliability is doubtful or the data concern bauxite occurrences of low grade or quite insignificant, of no importance whatsoever or without any potential prospect. During the proposed survey by a new method their more detailed revision may also be embarked upon, inasmuch as the countries concerned may require it.

As a first and rough approach to launching the proposed system of survey, distinction has been made on the map-sketches of the particular countries between areas which are already explored (partly or completely) and areas which are sparsely explored or totally unexplored, but which, considering their climatical, geomorphological and hydromorphological circumstances and their source rock characteristics, are believed to be worthy of the survey. By giving prominence to ancient continental shield areas, (cratons) attention is called to the need for separating here the laterites developed on the even geologically ancient rocks and the old surfaces from the laterites of peneplain or plateau type. In case of the former, the trends valid to laterites or bauxites associated with ancient surfaces and ancient rocks may be crucial for the forecast.

Both in principle and in practice the greatest bauxite potential is proper to those tropical developing countries (however reduced in size geographically as they may be, e.g. Suriname, Federal Republic of Guyana and French Guyana in South America or Guinea, Sierra Leone, the Ivory Coast and Ghana in Africa, and South Vietnam in Asia) which are situated, completely or for the most part, on *ancient shields (cratons)* or *micro-continental plates* (e.g. a part of South Vietnam). If the Tertiary and subrecent climatic conditions of these countries, their geology and morphological features were favourable for plateau laterite development, the discovery in these areas of important bauxite resources of marked influence on the global resources might even be expected.

After presentation of the sketch-maps of a few countries directly attached to them, some major bauxite areas of the particular countries are charted, as cut-outs, in greater detail as an example or in selected cases. Moreover, sketch-maps of single majo: bauxite plateaus are also appended (Fig. 27, 30, 40, 42, 50, 52). Such increased details added to selected cases will not disturb the clearness of the presentation and, on top of that, the few selected examples will make more clear the degree of resolution needed for the studies, for the survey to be carried out.

The outline map-sketches of the particular countries intended to serve as proposals to start with under the project contain in every case squares of 100x100 km (10 000 km^2) size which, properly fitted or with some minor overlapping, represent the areas recommended for the survey that are known to be identified or for which the climatical, geomorphological and hydromorphological data suggest that they are worthy of being surveyed (being promising for bauxite). Three big countries such as Brazil, India and Australia (here, because of the order of magnitude of the reserves, West Australia, Queensland and the Northern Territory are dealt with separately) are exceptions to the rule, the initial squares given for these being 500x500 km rather than 100x100 in size into which they, when needed, will have to be split up in a further step of the survey.

The series of map-sketches here presented are provided, for each continent, with a brief summarizing text, rather short as compared to the importance of the survey, thus being devoted to South and Central America, Africa, Asia, Australia and Oceania.

Because of the absence of tropical plateau-type laterite-bauxites in Europe and North America, these two continents are to be left out of the account. In case of S America, because of its expectable importance in the Globe's bauxite prospects, a short summarizing text is given by countries, having the largest laterite potentials.

SOUTH AMERICA

South America is supposed to be a continent having the world's largest plateau-type laterite bauxite resources. In terms of V. G. HILL–S. OSTOJIĆ's assessment (1981) of the bauxite resources, South America's possible bauxite potential, concentrated mainly in countries of the Guyana Shield (Federal Republic of Guyana, Suriname, French Guyana, Brazil, Venezuela and Colombia), accounts for about 40% of the Earth's total. Naturally, this is a preliminary estimate the reality of which may be corroborated or refuted by the results of exploration to be done in the coming decades. At any rate, the bauxite exploration results thus far available (Los Pijiguaos, Rio Trombetas, Jari and Paru Rivers, Nassau Mts, Lely Mts, Bakhuys Mts, Kaw Mts, etc) have proved the presence in the region of bauxite deposits belonging to the most significant plateau-type laterite-bauxites of the Globe. The areas concerned, as a rule, are covered by dense tropical forest, being rather desolate and difficult to reach and additional enormous bauxite resources are still to be expected in similarly forlorn areas, difficult to penetrate and devoid of any infrastructure. To assess all these and to harness them are tasks for the coming decades. Especially in Brazil, the Federal Republic of Guyana and Suriname is the future discovery of sizable bauxite resources to be reckoned with. South America is, no doubt, the continent, where, partly on account of its being unexplored, partly because of the difficulty of access to it and its lush tropical forest cover, there may be the greatest expectations as to adding a lot to the Earth's laterite bauxite resources potential.

Brazil

Covering a total area of 8.5 million km^2, this huge country occupies about the half of the South American subcontinent. Of this enormous area, a total of about 160–200 thousand km^2 may be promising for searches for laterite-bauxite reserves.

It is especially the northern part of the country, the Brazil portion of the Guyana Shield, that includes areas prospective for laterite-bauxite. Bauxite exploration in the 1950–1960's (ALCOA, Alcan, MRN) in the Amazon basin led to discovery along some tributaries of huge bauxite deposits (Rio Trombetas, Almeirim, Paru and Jari Rivers) which now can be boast of bauxite mines that are most important in the nation's bauxite industry (Trombetas River Project: an annual output of 3–5 million MT of bauxite). The developments the area under consideration is to undergo are enormous. Its mines have about over 600 million MT of bauxite reserves exploitable by open-pit mining. The bauxite grade, after washing, is good, being suitable for both domestic use and exports. Further exploration projects in the neighbourhood of the Jari and Paru Rivers and in the Paragominas area SE of Belém led to discovery of sizable bauxite reserves. In Amapa State and in the SE zone of the Brazil Upland, near Sorocaba, Poços de Caldas, Ouro Prêto Diamantina, Laginha, etc there are also great laterite-bauxite reserves awaiting exploration. In addition, climatic, water regime and geomorphological data suggest that there are a number of other areas, mainly plateau-type regions, that are to be prospected for bauxite in that country. All of the estimated 5–6 thousand million MT or so of bauxite reserves so far identified are laterite-bauxites. As estimated by V. G. HILL–S. OSTOJIĆ (1981), the bauxite potential of Brazil is about 38 thousand million MT which includes both the identified bauxite reserves and the hypothetical commercial raw material for aluminium which does not hit the present-day beneficiation standards, but which may still be rated as bauxite ore. The areas with prospective potential resources and the ones with already explored and identified or partly explored reserves are shown in Fig. 5 and 6.

Venezuela

It is the S and SE parts of this country that belong to the ancient Guyana Shield. Bauxite exploration projects in the 1970's led here to discovery of one of the largest bauxite deposit complexes, at Los Pijiguaos, where an efficient bauxite mining industry has been developed recently (Bauxiven) (Fig. 7., 8). The bauxite areas in the E and SE parts of the country (Upata–Nuria) are also promising, still having considerable bauxite reserves (Gran–Sabana). Preparations for developing Venezuela into a "big bauxite power" are in progress (bauxite mine, alumina plant and smelter) (Bauxiven, Los Guaicas, Ciudad Guyana). The bauxite potential of the country is quite significant (resources as large as 1–6 thousand million MT being quite possible), mainly in the Guyana Upland.

Lately inaugurated, the Guri Dam, with a huge artificial lake and a hydroelectric power station based thereon, provides the industry with a wealth of very cheap electric energy which is in harmony with the bauxite, alumina and aluminium industry plans for exploitation of both the nearby (Los Guaicas) and the more remote (Los Pijuguaos) bauxite reserves.

Federal Republic of Guyana

The Federal Republic of Guyana lies overwhelmingly on the ancient Guyana Shield. Her climatical and topo-morphological characteristics were very advantageous for the development of laterite-bauxite. The bulk of the identified, explored bauxite reserves is concentrated in the so-called "Guyana Bauxite Belt" (Mackenzie, Barbice and Essequibo Rivers, etc) (Fig. 9). The survey of the laterite-bauxite plateaus of the hinterland areas and the exploration of their bauxite resources are, for the most part, still to be done (Blue and Oko Mts, Pakaraima Mts, etc). According to some estimates (V. G. HILL–S. OSTOJIĆ, 1981), Guyana has enormous laterite-bauxite reserves which, however, very widely vary in grade (about 10–25 thousand million MT), chiefly on the hinterland plateaus, i.e. in mountainous regions very difficult to penetrate. To discover these large reserves of bauxite and to explore them remains a task to carry out in the coming decades.

Suriname

Although looked at as a country of very small area as compared to her giant neighbour in South America, Suriname is reckoned with, nevertheless, as a big bauxite power on a global scale. On account of marketing and other difficulties, her bauxite output has dropped in latest years from an original figure of 6 million MT per year to as little as 2 million MT. This situation, however, is in no proportion to her potential resources. To this date, mainly the bauxite deposits, well-known for a long time now, of the Guyana Bauxite Belt close to the coastal zone (Onwerdacht, Paranam, Moengo, Lelydorp, etc) have been exploited and the mining operations have not been extended as yet to the huge, recently explored bauxite reserves of the hinterland plateaus (Bakhuys Mts). Future development programs have envisaged to launch the large-scale exploration of the plateaus and to discover and explore the bauxite resources of further hinterland plateaus (Nassau Mts, Lely Mts, Kayser Mts, etc). The individual experts widely vary in opinion as to the potential resources (from 0.6 thousand million to 10 thousand million MT) (GY. BÁRDOSSY 1983, H. R. POLLACK 1980, V. G. HILL–S. OSTOJIĆ 1981). Anyway, that Suriname still has a plateau-type laterite-bauxite potential of thousand million MT magnitude can be taken for almost sure. The distribution of the laterite-bauxites to be expected is shown in Fig. 10.

French Guyana

An overseas department (département outre-mer) of France, French Guyana, in the light of the bauxite exploration results so far available (mainly by BRGM and SODEMI), is reckoned with as a South American country with considerable bauxite resources. Only on minor plateaus near the coastline (Kaw Mts, Roura Mts) has there been some bauxite exploration on a larger scale, though traces of laterite-bauxite are known from plateaus in the more internal regions of the country as well (Mahury Plateau, Mitaraca, etc) and, here, by analogy with other areas, enormous bauxite resources are surmised. Some authors believe (V. G. HILL–S. OSTOJIĆ 1981) that the country has a bauxite potential of about 1.7 thousand million MT. The bulk of these resources, however, occurs in hinterland plateau areas covered by a lush forest vegetation, access to which because of the lack of any infrastructure is very difficult (Fig. 11).

Colombia

Discovered in the 1970's (Morales–Caibio area in Cauca province), the bauxite deposits of Colombia as a result of the exploration that has intensified ever since, have reached, in recent years, an order of magnitude of 100 million MT in resources (about 360 million MT), and additonal potential resources are hidden, especially in the E part of the country, in the Guyana Shield area. The E and SE regions have no infrastructure, though the potential resources there are larger (Fig. 12).

Other South American countries to be reckoned with

Paraguay, Argentina, Bolívia and Chile may be taken into account as countries with minor resource-indications (Fig. 13, 14).

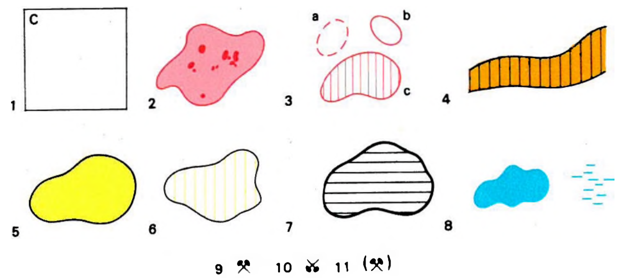


Fig. 4 Legend for the outline map-sketches of the countries

(1) 100x100 km and/or 500x500 km squares covering known and/or potential bauxite areas recommended for survey and their symbols, (2) explored (known) bauxite deposit (red), explored or partly explored bauxite area (pink). 550–610=altitude a.s.l. of plateau levels (m), (3) probably potential bauxite area recommended for survey (a), the same, totally unexplored (b) or just very poorly explored (c), (4) bauxite zone, (5) area of ancient shield, (6) area of microcontinental plate, (7) disputed area, (8) sea, lake, marsh, (9) bauxite mine in operation, (10) abandoned mine with depleted reserves, (11) bauxite mine in project

Fig. 5 Brazil

Source rock: gneiss, crystalline schist, amphibolite, phonolite, phonolite-porphyrite, nepheline syenite, nepheline-kankrinite syenite, eudialite-nepheline syenite, greissoid eudialite-nepheline syenite, granite, micaceous clay, tinguaite, foyaite

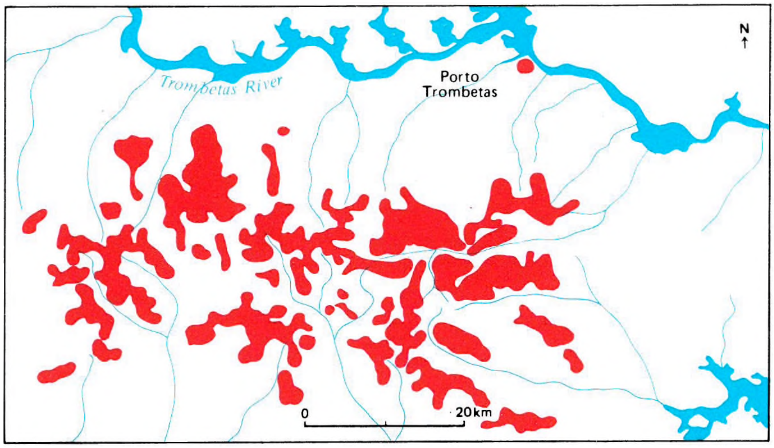


Fig. 6a The bauxitic plateaux of Porto Trombetas

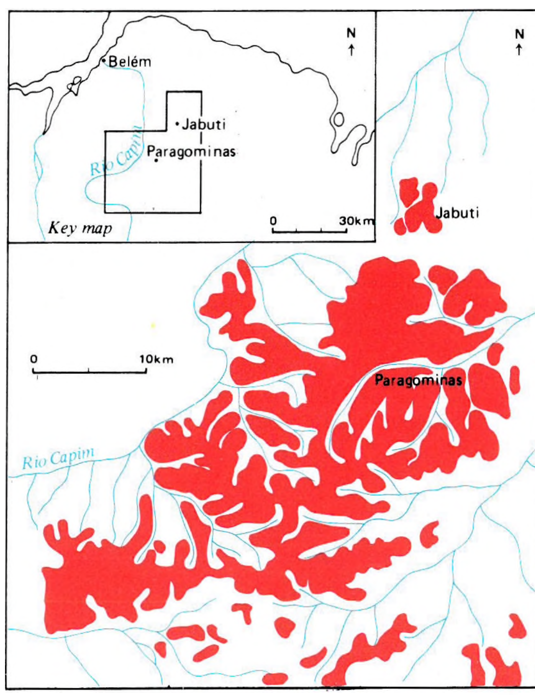


Fig. 6b The bauxitic plateaux of Paragominas

Fig. 6 Major bauxite occurrences in Central and Southern Brazil (After G. H. PATTERSON 1967)

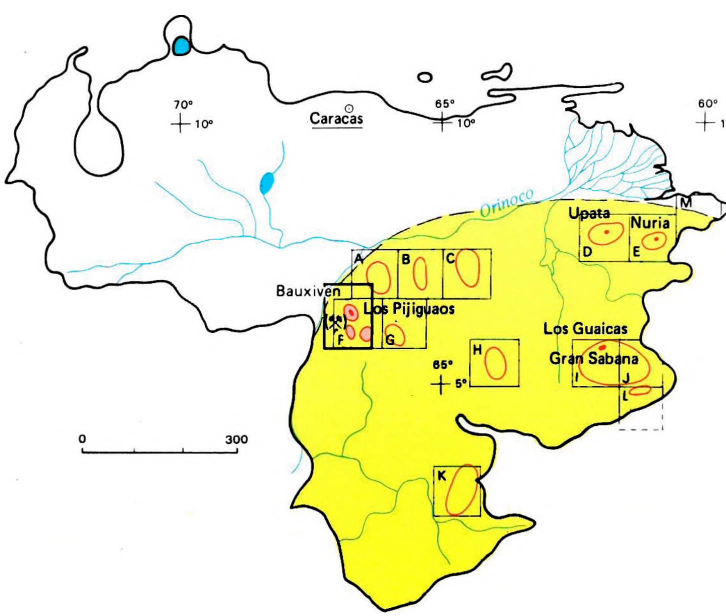


Fig. 7 Venezuela

Source rock: sandstone, granite, granodiorite, dolerite, diabase

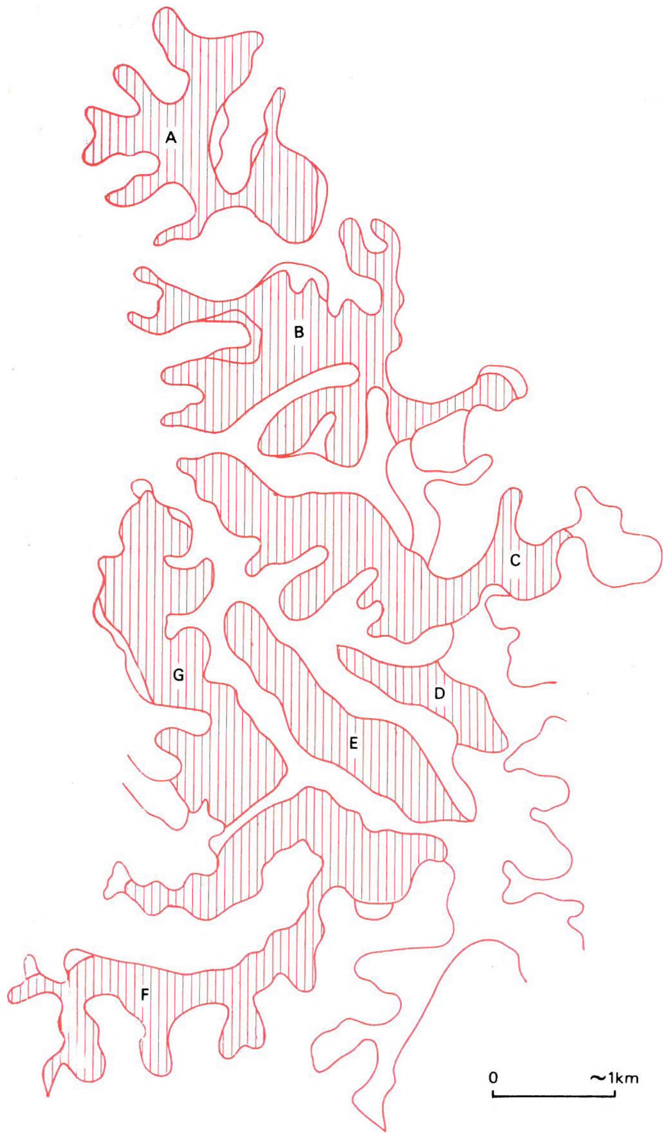


Fig. 8 Detail from the N plateau complex of Los Pijiguaos (After RATMIROFF 1978)
A–G=explored sub-plateaus and reserve calculation blocks

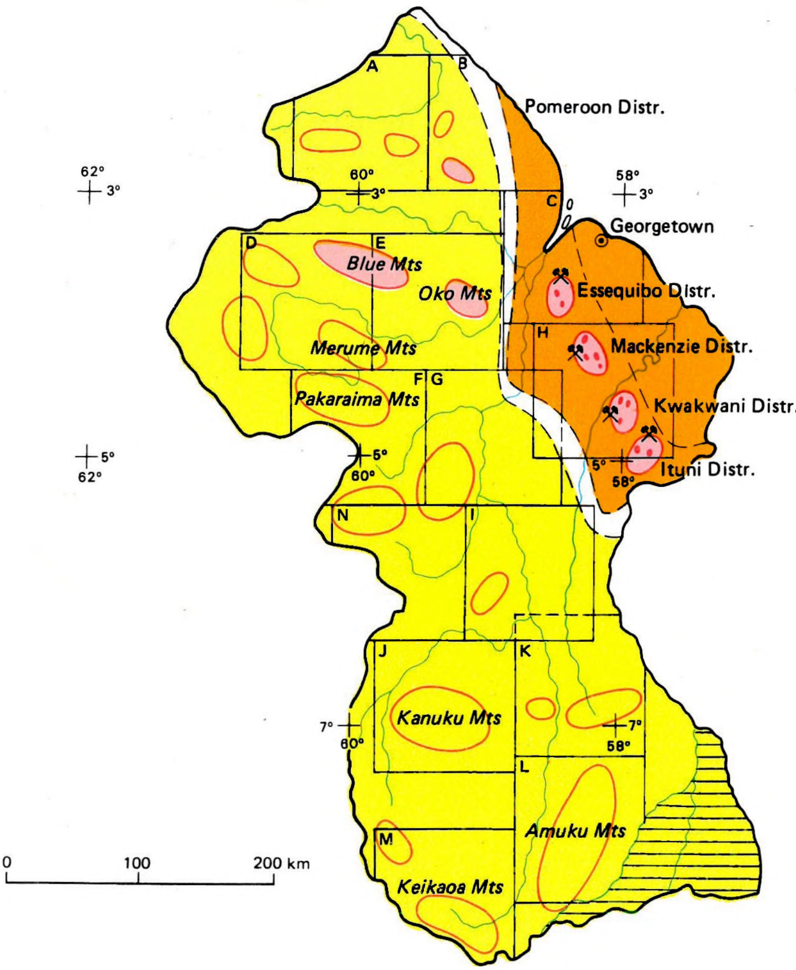


Fig. 9 Federal Republic of Guyana

Source rock: granite, granodiorite, meta-greenstone, crystalline schist, diorite, epidiorite, dolerite, micaceous clay, kaoliniferous clay

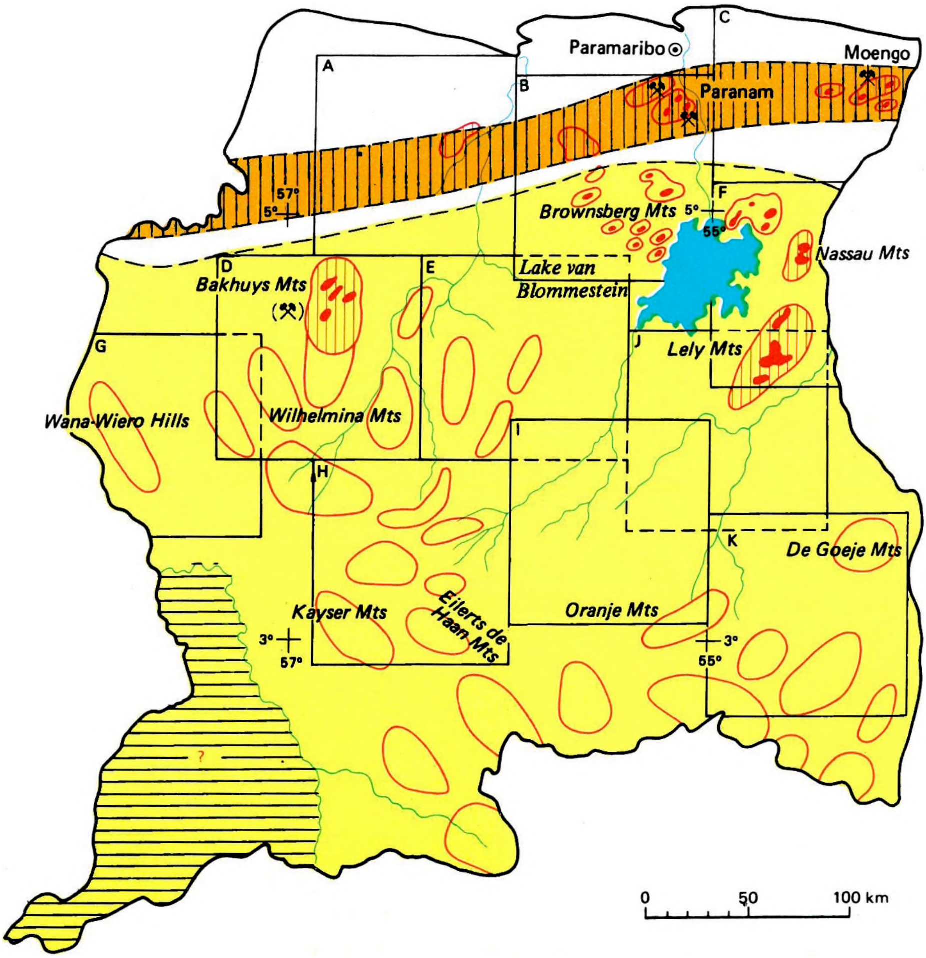


Fig. 10 Suriname

Source rock: olivine basalt, crystalline schist, gabbro, anortosite, gabbronorite, granite, granodiorite

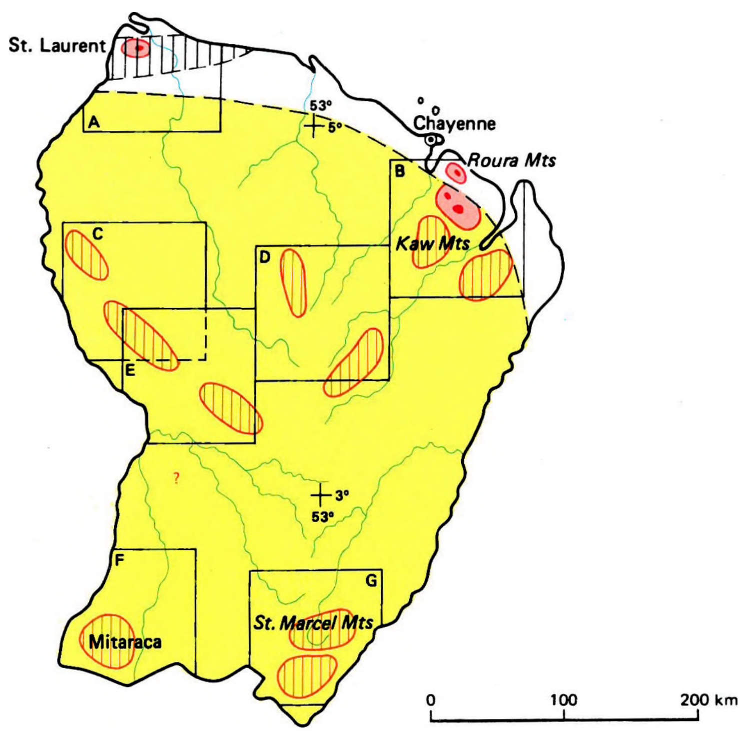


Fig. 11 French Guyana

Source rock: crystalline schist, meta-greenstone

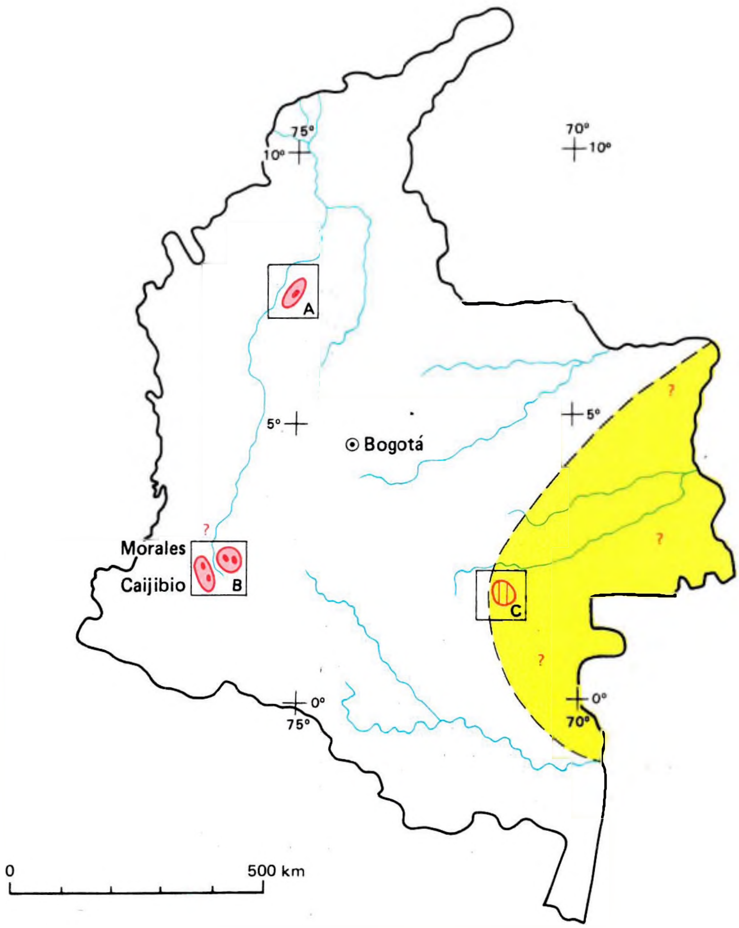


Fig. 12 Colombia
Source rock: andesite, andesite agglomerate and tuff

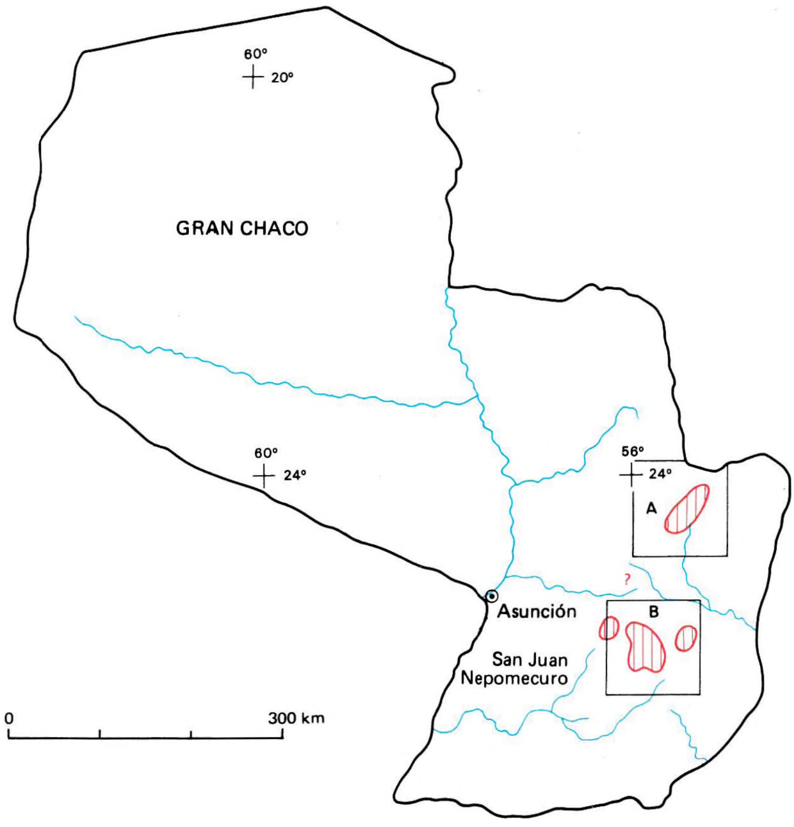


Fig. 13 Paraguay

Source rock: nepheline syenite, shonkinite, basalt

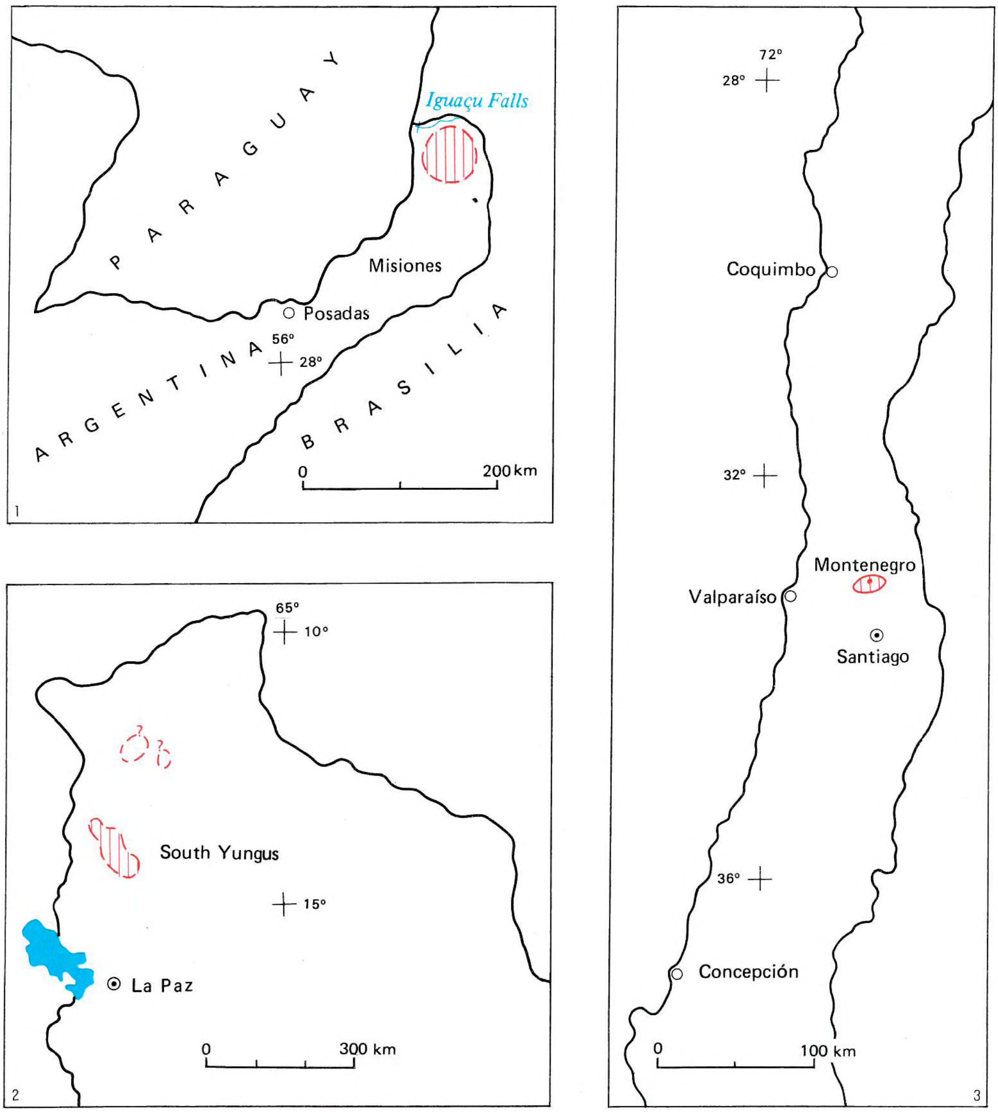


Fig. 14 Other countries to be taken into account (South America)

1 Argentina (Misiones province), **2** Bolivia (South Yungus), **3** Chile (central part)

CENTRAL AMERICA

In this region there is no much hope to enlarge the potential plateau-type laterite-bauxite resources. Although there are possibilities of this kind in some areas in the S of Mexico, the sporadical searches carried out so far have detected the presence of too young lateritic formations that are associated mainly with volcanic pyroclastics in which there is little hope, if any, for discovering genuine and sizable laterite bauxite ore bodies. The same holds true of areas in Salvador (Fig. 15) and Honduras with just a few minor occurrences. In the S of Cuba (Moa Mts, Cantarana, Oriente province) too some traces of bauxite have been discovered which also prove that the laterite sequence is too young to have been able to yield a sizable bauxite deposit. At any rate, these traces too will have to be revised so as to make the judgement of the plateau-type laterite bauxite potential of the region more realistic.

In the region under consideration, *Costa Rica* (Fig. 16) is that country in which there is an estimated 150 million MT or so of laterite-bauxite reserves (Valle del General near San Isidoro), but the exploitation of these reserves is still dependent on further economic considerations. An all-round assessment of the bauxite potential is still missing.

The traces of bauxite known from *Panama* (Fig. 17) too bear witness to the fact that there was and, moreover, there is even at present some laterite-bauxite formation under way and this fact makes the discovery of potential bauxite resources quite plausible. The rough topography, the dissected morphology and the very high amount of annual rainfall (~3000 mm) do not favour the formation of large deposits or their preservation, respectively.

Moderate to minor laterite-bauxite discoveries, as a potential resource, may be reckoned with, mainly in Panama, Costa Rica, *Honduras* and *Nicaragua* and maybe also in *Belize* (Maya Mts) and perhaps in some parts of *Guatemala* as well, or in the S of *Mexico.* As suggested by data from obscure sources, there are traces of bauxite on the Island of *Dominica,* mainly on volcanic, basalt or basalt tuff, plateaus of 600 to 900 m altitude in the interior of the island, as well (Fig. 18).

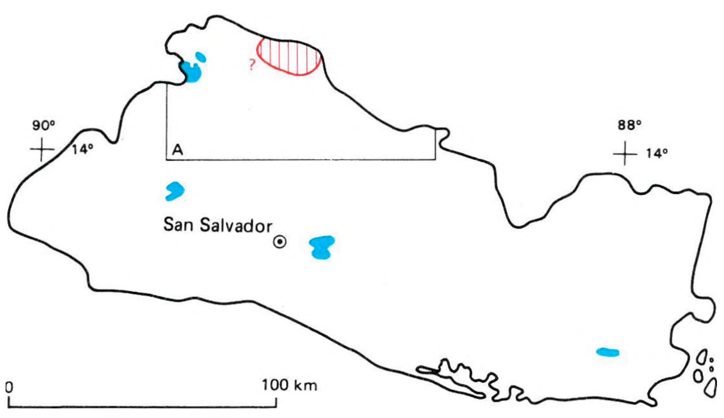


Fig. 15 Salvador

Source rock: ?basalt, basalt tuff, (andesite)?

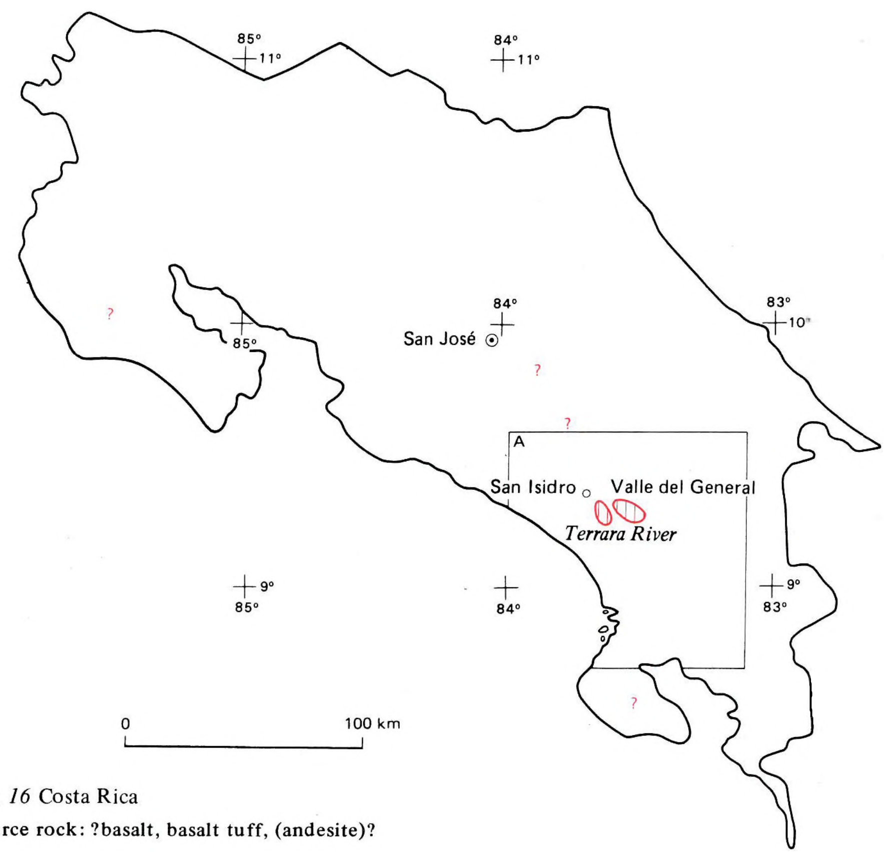


Fig. 16 Costa Rica
Source rock: ?basalt, basalt tuff, (andesite)?

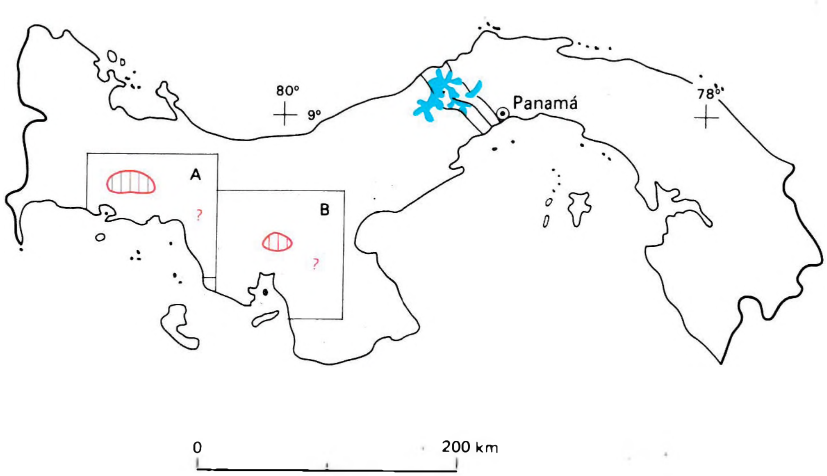


Fig. 17 Panama
Source rock: ?basalt, basalt tuff, (andesite)?

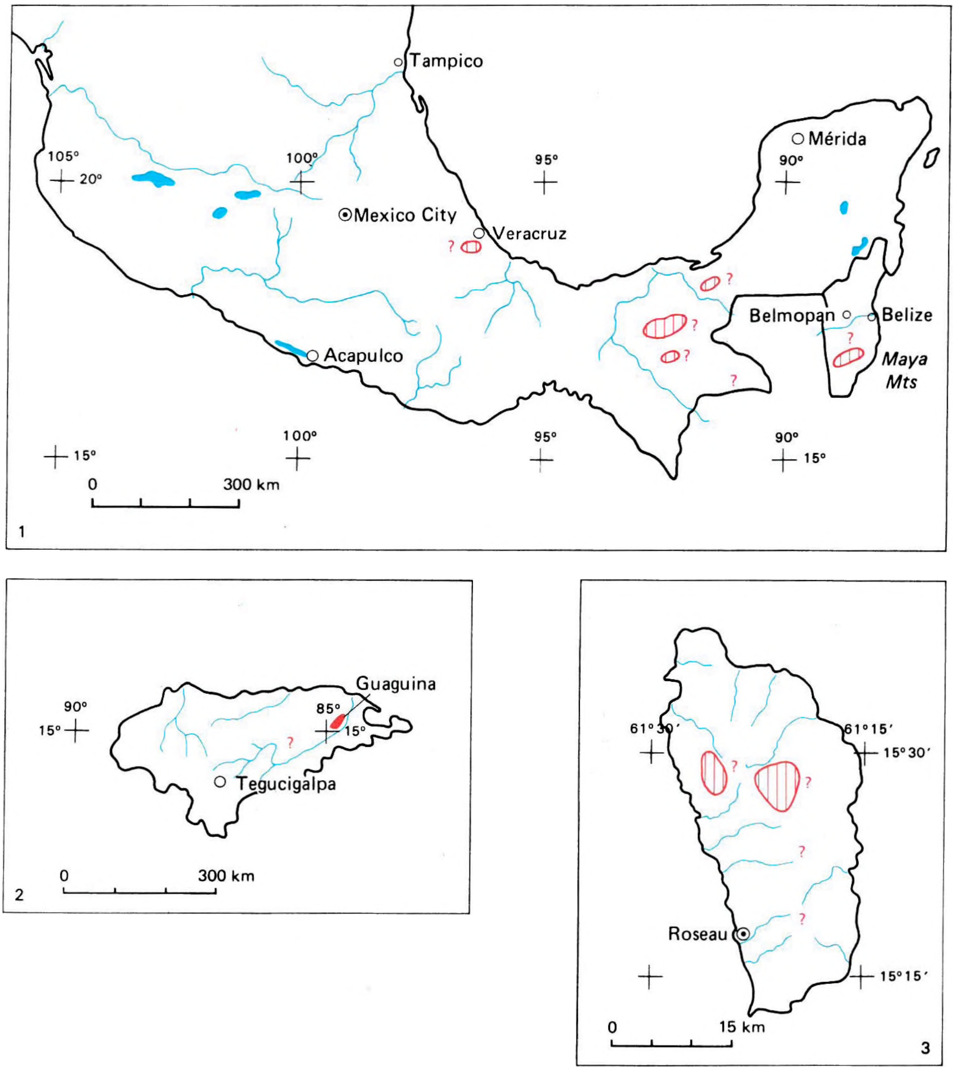


Fig 18 Other countries to be taken into account (Central America)
1 S part of Mexico and Belize, **2** Honduras, **3** Dominica I.

AFRICA

In Africa only laterite-bauxites have so far been known to occur, the bulk of them on plateaus. The potential resources too are hoped to be discovered on these plateaus.

The African countries having quite significant bauxite resources belong to the tropical rain forest and partly savannah belt traversing the central parts of the continent. Out of these, the bauxite reserves of the *Republic of Guinea* are crucial (>10 thousand million MT) in W Africa, several other countries also having considerable resources (e.g. *Cameroon, Ghana, Sierra Leone, B. Guinea*). In East Africa and in the SE of the continent, the bauxite resources in some countries, excepting Madagascar, are moderate in importance; in other countries, on account of the very poor and primitive exploratory facilities available, there are merely some indications suggesting a moderate bauxite potential to be expected *(Malawi, Zimbabwe, Mozambique).* The occurrence of laterite-bauxite is known from a few countries of Central Africa as well and this fact may put forward the probable worthiness of launching further bauxite exploration projects in these areas *(Zaire, Equatorial Africa, Gabon, People's Republic of the Congo, Uganda).* Earlier discovered bauxite resource-indications or deposits and, on continued exploration of these, possibilities for discovering an added bauxite potential are available in *Niger, Chad, Nigeria, Togo, the Ivory Coast, Liberia, Mali* and *Senegal.* Of these only the bauxite reserves on the SW border of Mali are important (Sitadina). The existence of a bauxite potential is not excluded in the case of the southermost part of Sudan, some parts of *Ethiopia* and some regions of *Rwanda-Burundi, Zambia* and *Angola* either. The laterite-bauxite found in the *Republic of South Africa* is one of the oldest laterite-bauxites ever discovered on Earth and this leads to the idea of some bauxite prospect in that country, regardless of her not being favourable anymore, from the climatic point of view, for lateritization.

All in all, especially in those countries of the African continent underlain by ancient shields, there are still very significant unexplored laterite-bauxite resources to reckon with. The total potential resources of these bauxites may attain even a magnitude of thousand million MT. The *Congo, Ghana,* the *Republic of Guinea, Nigeria, Cameroon, Zimbabwe* and *Madagascar* are, in the first place, the countries, where considerable growth increments to the potential resources may still be added in the years to come. In these countries the availability of only a partial infrastructure can be spoken of. In a good deal of the potential bauxite areas the infrastructure ought to be brought subsequently into a pristine environment even in the case, if the supposed resources were corroborated. This circumstance, especially in the more inland areas, far away from the coastline, does not stimulate research or exploration, the less so does it give any impetus to mining developments in bauxite deposits of medium or small size. Long-term development programmes, however, must already envisage the exploration of these possible resources, potential inland bauxite deposits as they may represent (Fig. 19–36).

The total potential laterite-bauxite resources of Africa may possibly account for about 20–25% of the Globe's total.

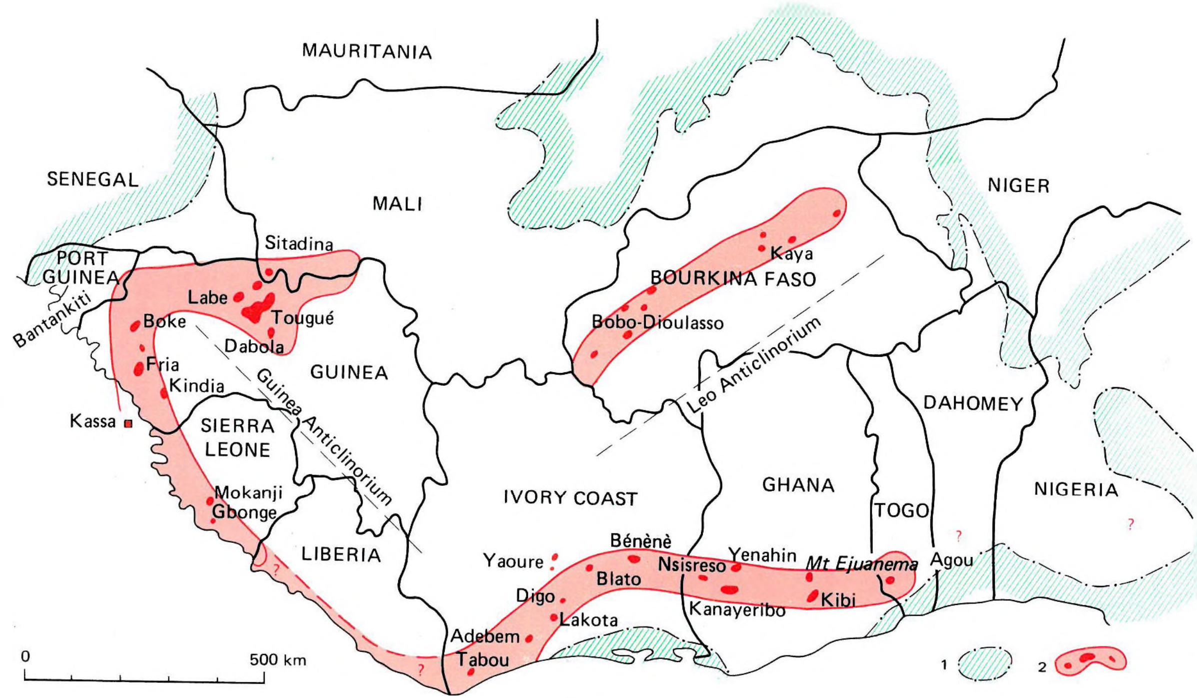


Fig. 19 Bauxite zones of West Africa (After L. ZANONE 1971)
1 Cretaceous–Eocene basins, **2** bauxite zone with bauxite occurrences

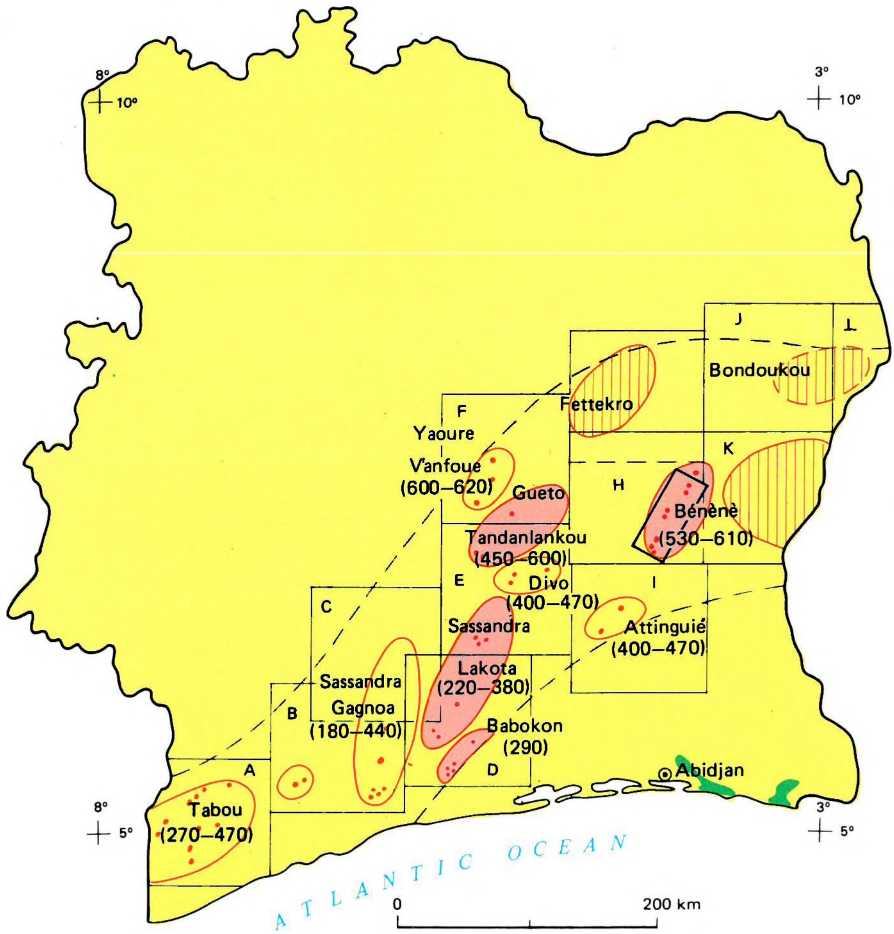


Fig. 24 The Ivory Coast

Source rock: diorite, granite, granodiorite, diabase, crystalline schist, phyllite, dolorite. Cut-out in Fig. 25.

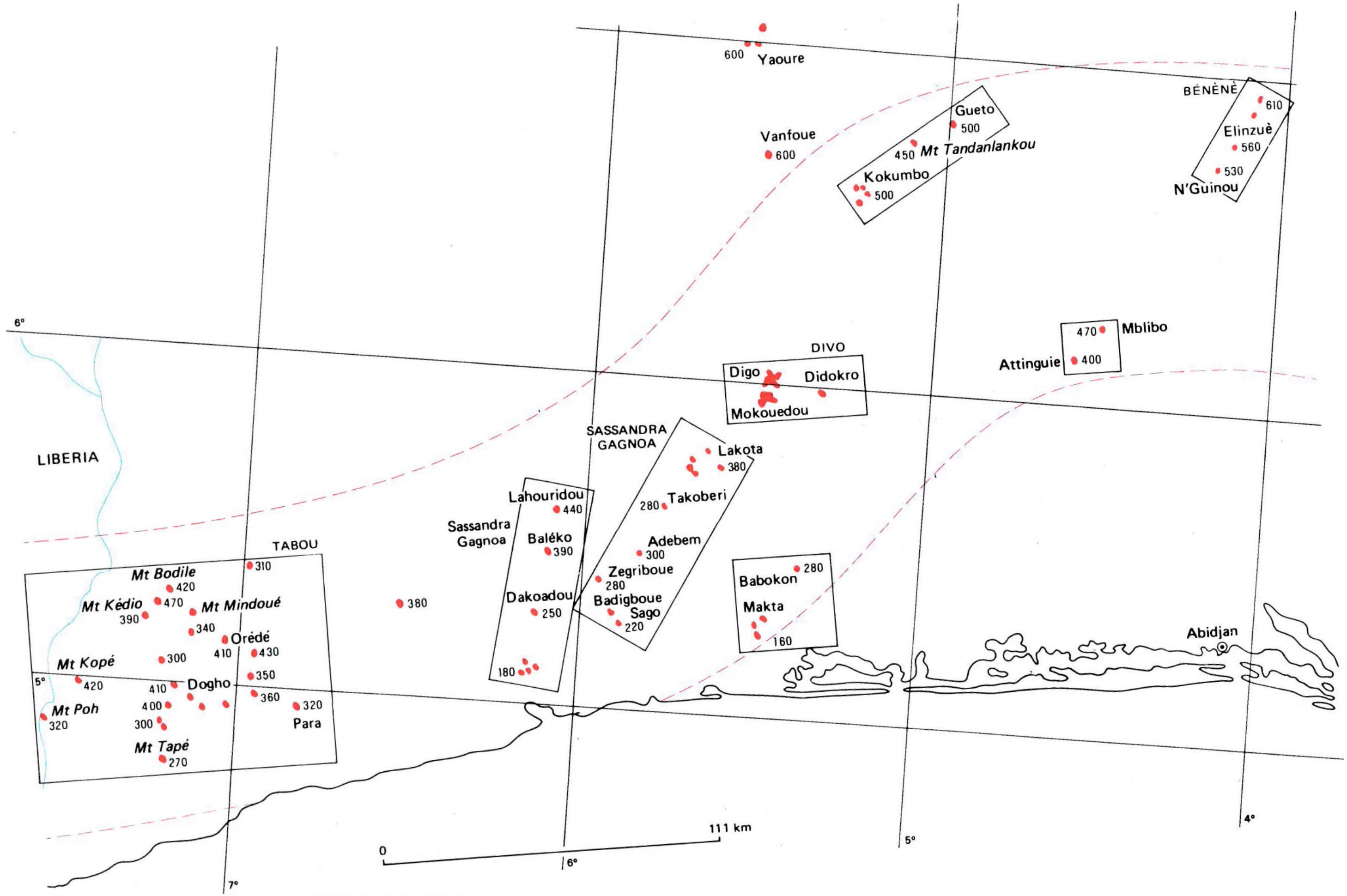


Fig. 25 Sketch map of the deposits of the Ivory Coast laterite bauxite zone

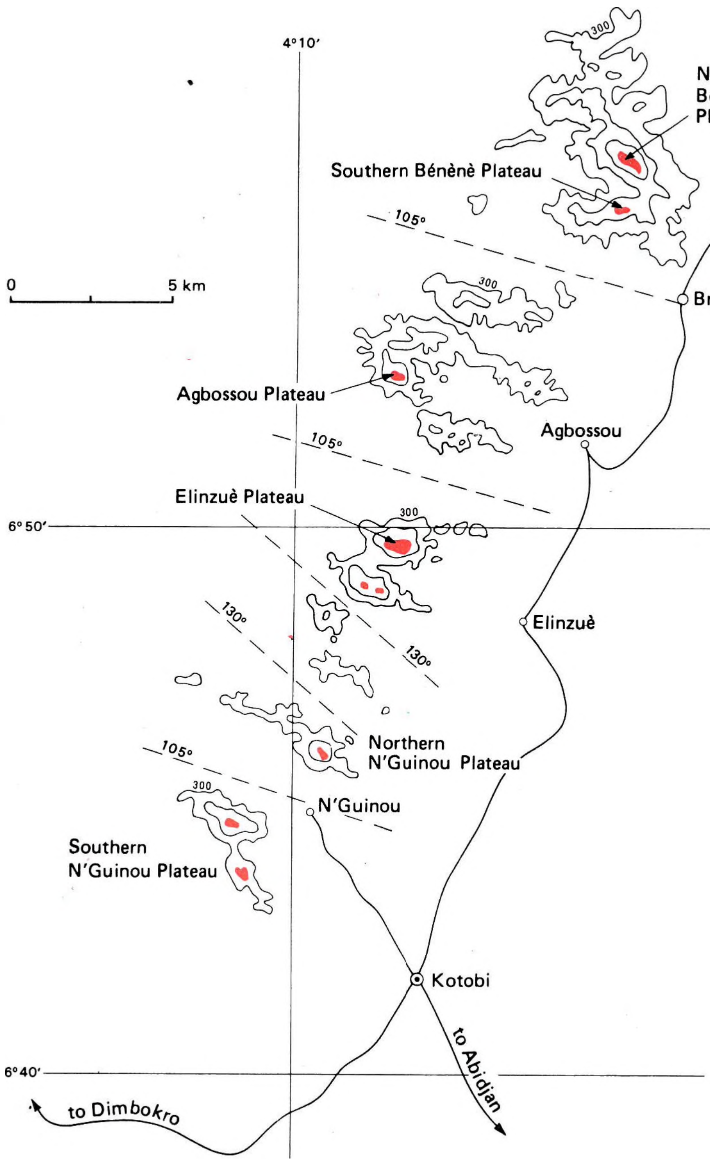


Fig. 26 Bénènè exploration area

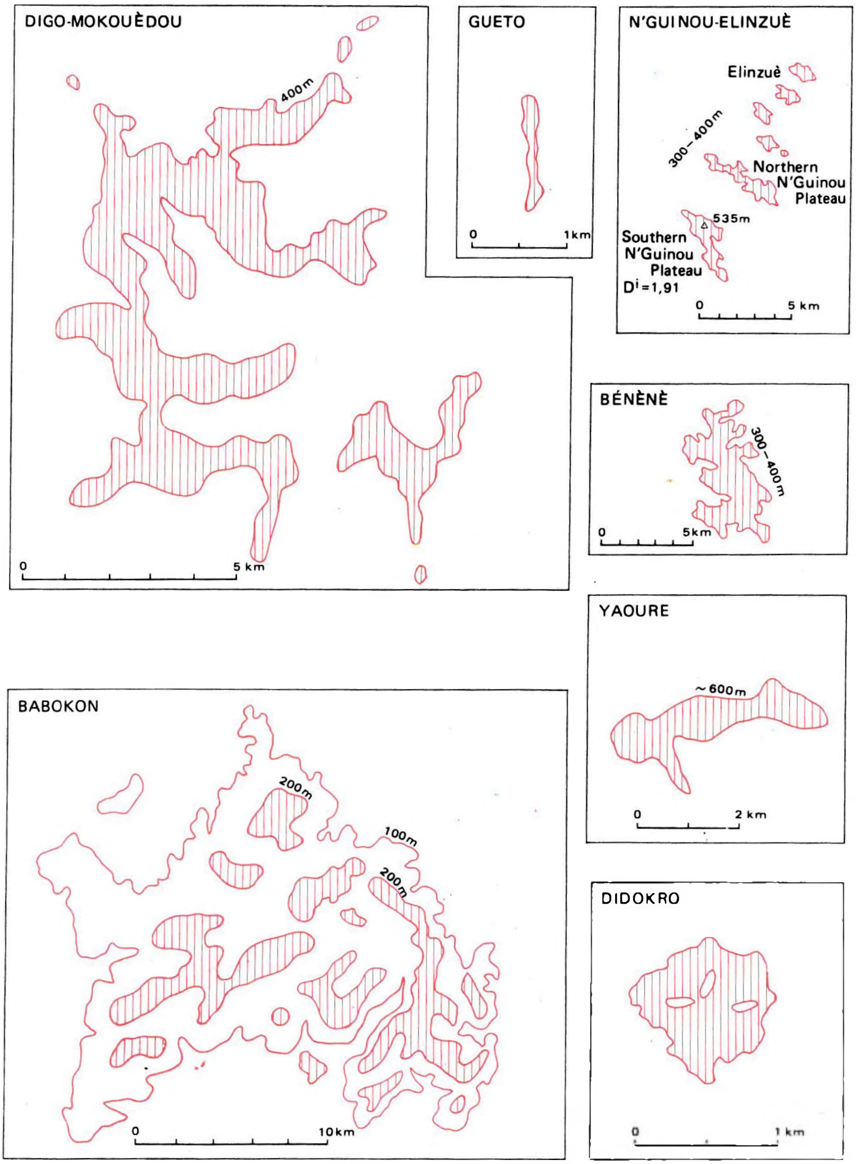
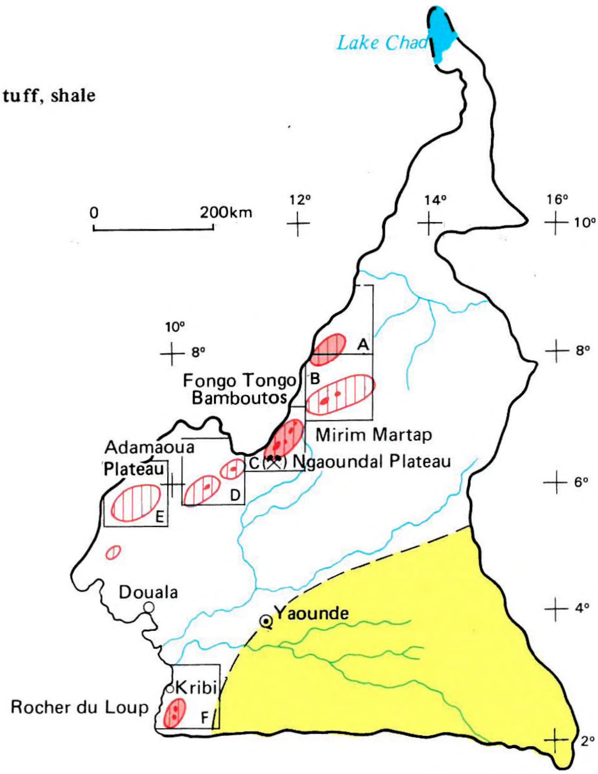


Fig. 27 The Ivory Coast (After L. ZANONE 1971)

Fig. 28 Cameroon

Source rock: basalt, trachyte, trachyte tuff, shale



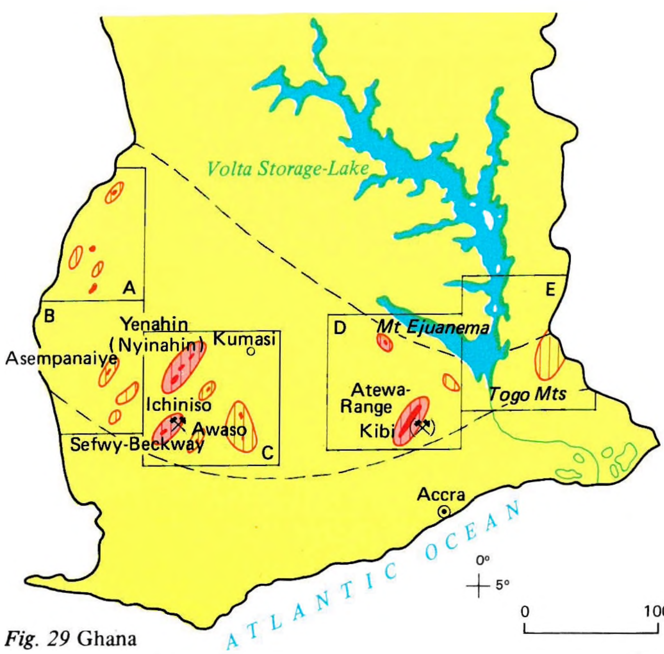


Fig. 29 Ghana

Source rock: phyllite, granite, greywacke, chloritic calc-schist, sandstone, shale, meta-greenstone, amphibolite, andezite, dacite, dacite porphyry, granodiorite, diabase, gabbro, pyroxenite

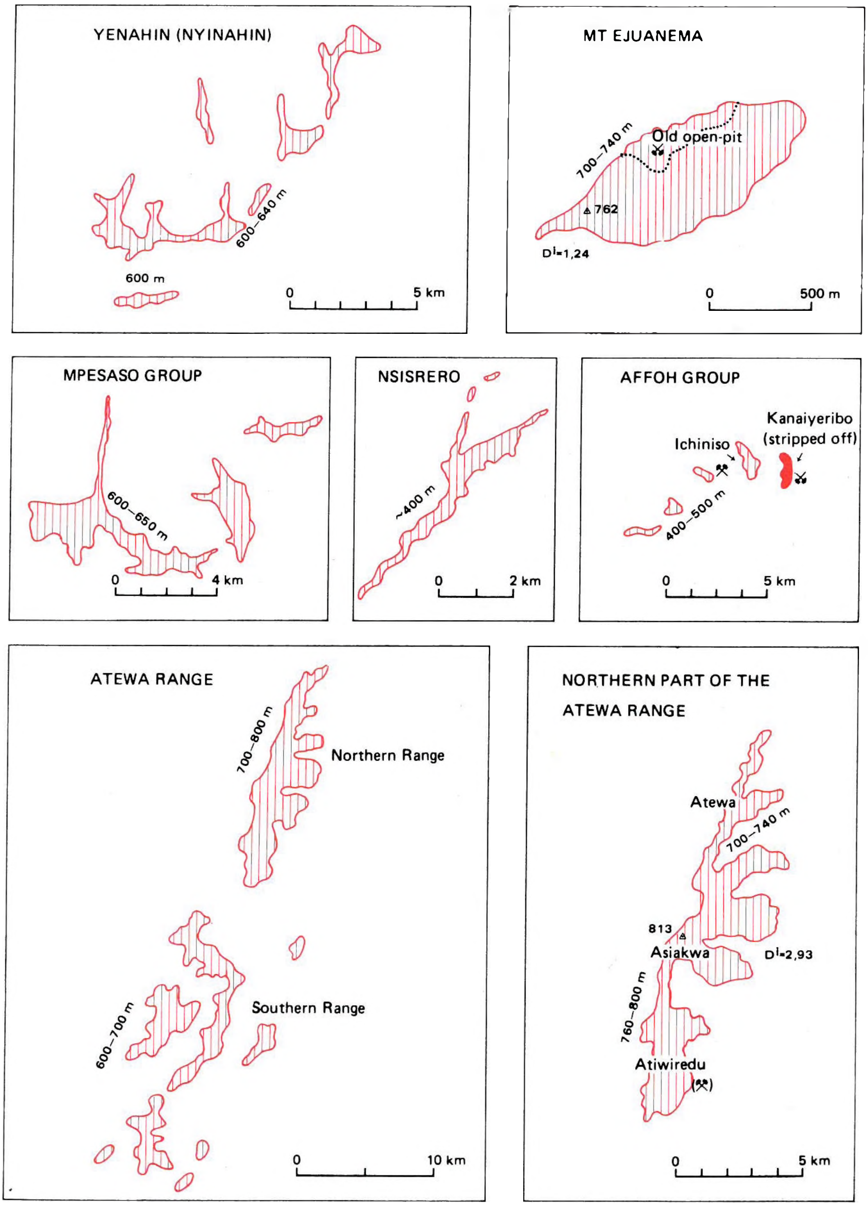


Fig. 30 Details about the deposits of Ghana (Fig. 29) in the light of the results of exploration carried out for the Ghana Geol. Surv. [W. G. A. COOPER (1936), G. O. KESSE, E. SZABÓ (1967), KAYSER and BACO (1963–1971) and BASCOL (1971–1973)]

Fig. 31 Block diagram of the bauxite deposit of Mt Ejuanema, Ghana (E. SZABÓ, 1975)
A small single plateau. Explored in detail (82 boreholes) in 1966–67 by the Ghana Geological Survey
(1) Bauxite, (2) laterite, (3) redeposited bauxite and laterite, (4) supposed ancient fault

Basic data:

Ground area of plateau: 0.7 km^2
Bauxite coverage: 62%
Mean annual temperature: ~23°C
Mean annual amount of precipitation: ~1800 m/m
Altitude a.s.l.: 750–762 m
Elongation index: 2.9
Index of dissectedness: 1.24
Expected (modelled) geological reserves (approved of in 1974): 1.1 mi. MT
Ore grade: 47.7/4.2/23.0% Al_2O_3 (SiO_2) Fe_2O_3
Underlying rock: Upper Volta sandstone and sandy shale

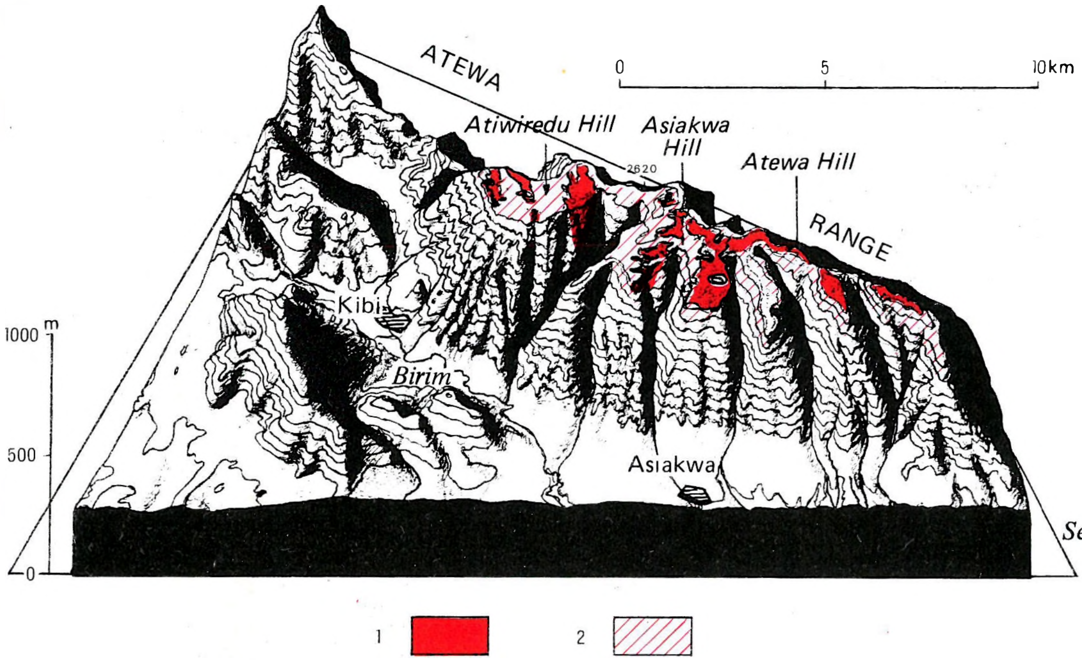


Fig. 32 Sketchy block-diagram of plateau-type laterite bauxites; Kibi, Ghana (G. O. KESSE – E. SZABÓ, 1975)
Plateau complex of medium size, reconnoitred by BACO 1957–58, KAISER 1964–65, Geological Survey (Ghana) 1966–69, BASCOL 1972–73, G. O. KESSE – E. SZABÓ 1975)

(1) Bauxite, (2) laterite

Basic data

Ground area of plateau: 22.6 km^2
Bauxite coverage: 42%
Mean annual temperature: ~22°C (at 800 m a.s.l.)
Mean annual amount of precipitation: 1900 – 2000 mm
Altitude a.s.l.: 750 – 810 m
Index of dissectedness D^i: 2.96
Expected (modelled) geological reserves: ~90 mi. MT
Ore grade: ~44/3/27% $Al_2O_3(SiO_2)Fe_2O_3$
Underlying rock:

Lower Birrimi: phyllite, greywacke, tuffs
Upper Birrimi: chloritic calc-schist, greenstone and phyllite
Post-Birrimi: biotite granite, biotitic schists, amphibolite, dacite, porphyry, granodiorite, gabbro and pyroxenite

Plateau-type laterite-bauxites are known to occur only in those countries of the continent belonging to the tropical climatic belt. Of these, the most wealthy reserves are found in *India* (Fig. 37 to 40) and the *Soc. Republic of Vietnam* (Fig. 41, 42), though in this latter the regular exploration projects had to be delayed till 1976, after the S and N parts of the country had been united. At any rate, the preliminary results and estimates are quite promising. In India, the large bauxite plateaus, mainly those in Orissa-Andhra Pradesh states (the eastern Ghats), now concentrate more than 2.5 thousand million MT of bauxite. These plateaus are still being explored even at present. Laterite-bauxites are known, in addition, from a number of other regions of India (Fig. 40).

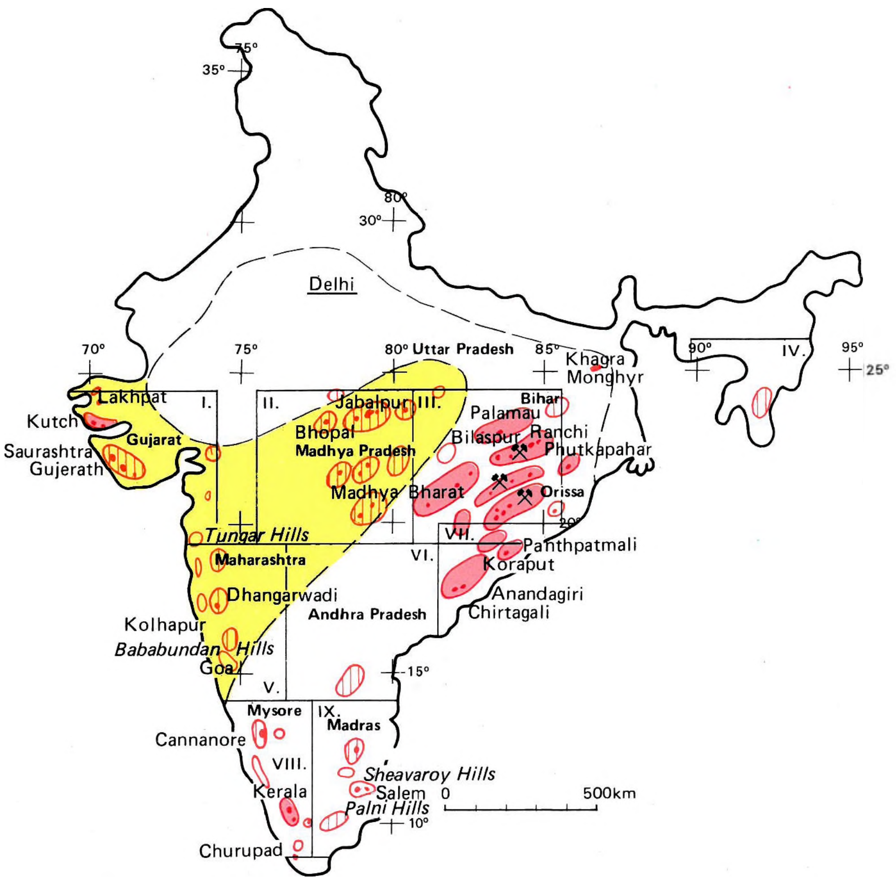


Fig. 37 India

Source rock: Deccan trap-basalt—basalt tuff, Malwa trap-basalt, khondalite, charnokite, graphite schist, leptinite (Shevaroy Hills)

On top of that, India possesses a wealth of thus far unexplored laterite-bauxite resources with a potential that may hit the thousand million MT magnitude.

Malaysia (Fig. 43) and *Indonesia* (Fig. 44), though moderately endowed with explored bauxite reserves, as far as the author's present-day knowledge goes, from a region of quite considerable bauxite potential to explore. Because of the jungle vegetation and

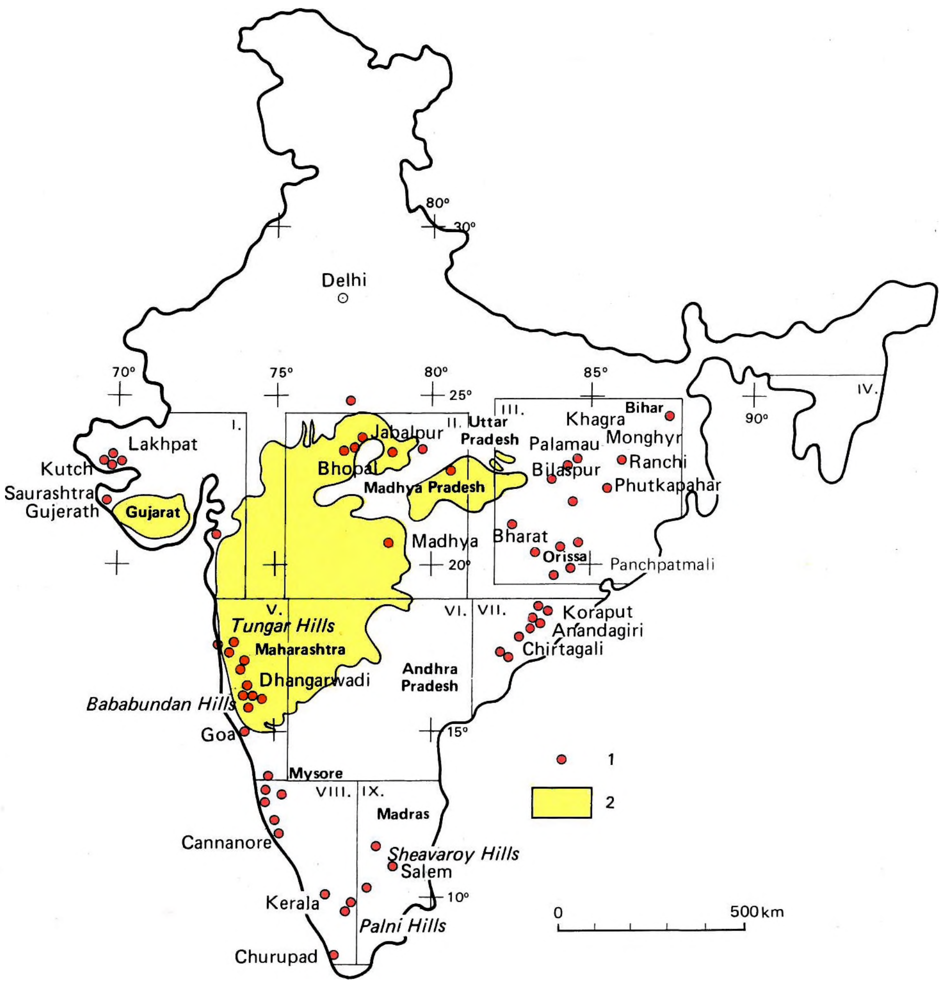


Fig. 38 Paleogeographical distribution of Lower Tertiary bauxite belts in India
(1) Bauxite deposits, (2) Deccan trap (After I. VALETON 1972)

Fig. 39 Sketchy outline map of bauxite occurrences in India

(1) Bauxite deposits, bauxite regions and bauxite zones with reserves of >500 million MT, (2) deposits, zones with 100–500 million MT of reserves, (3) deposits with 10–100 million MT of reserves, (4) minor occurrences with <10 million MT of reserves

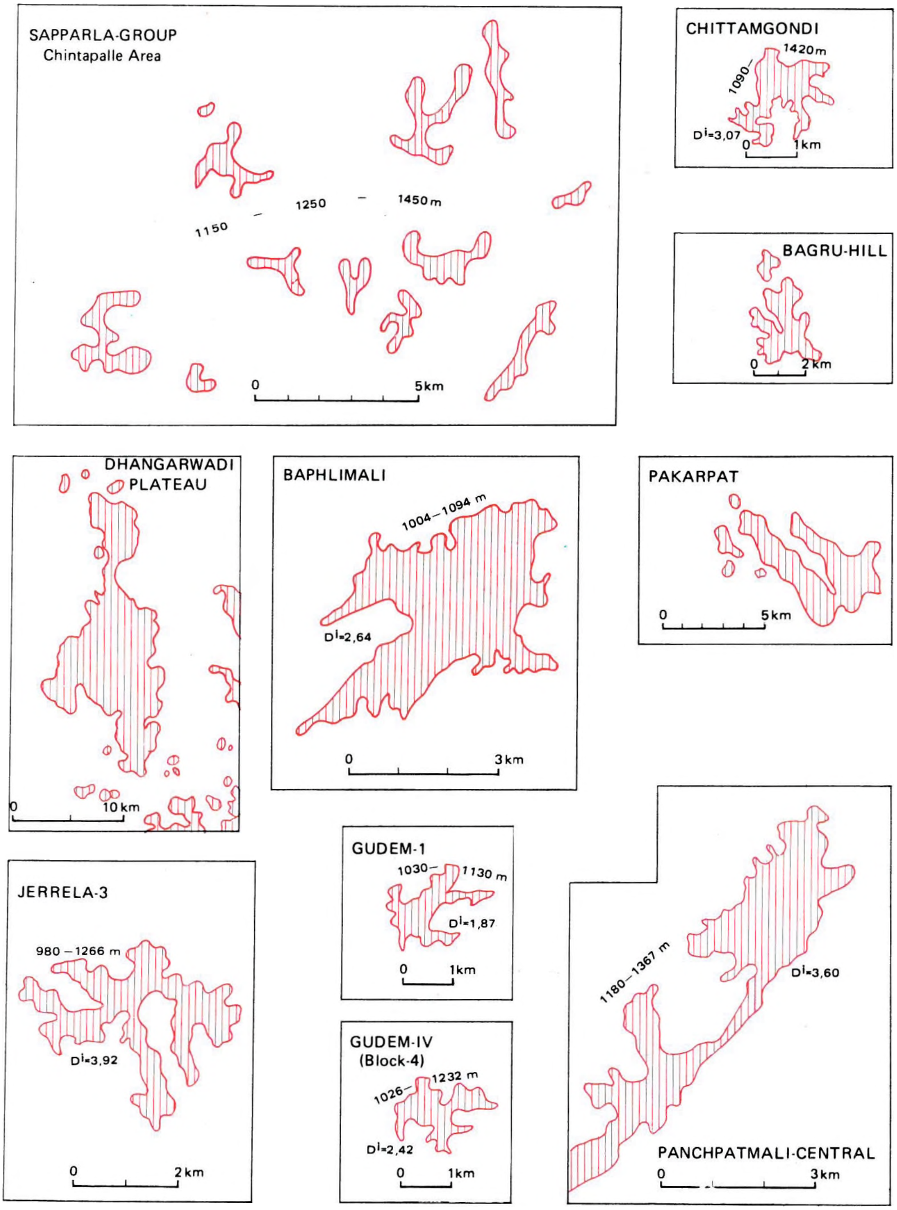


Fig. 40 Details about the bauxite deposits of India. Based on research conducted by the Geol. Surv. of India (After I. VALETON, M. G. RAO and RAMAM, GY. BÁRDOSSY)

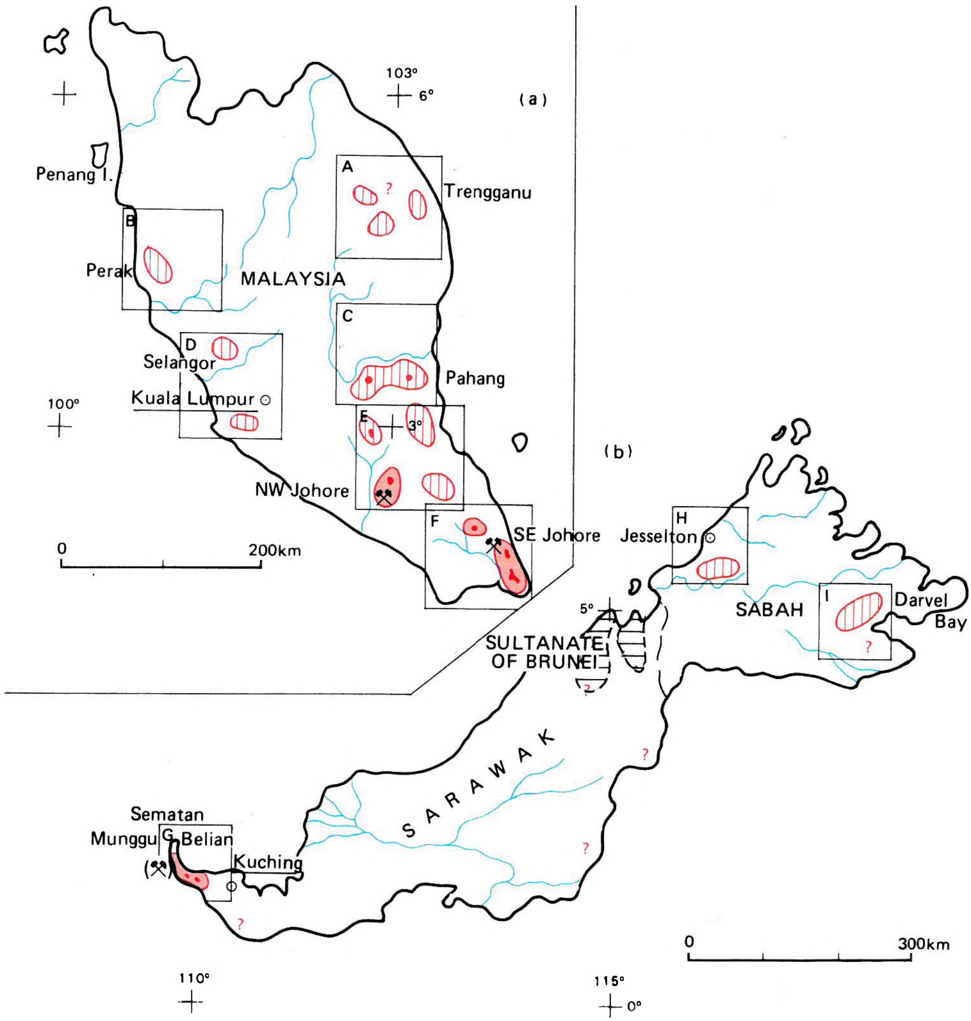


Fig. 43 Malaysia

Source rock (a): andesite, rhyolite tuff, trachite, hornfels, crystalline schist, granite, micropegmatite, pyrophyllite, graphite-muscovite quartz schist, leucite-tephrite, nepheline basalt, (b): basalt, basalt tuff

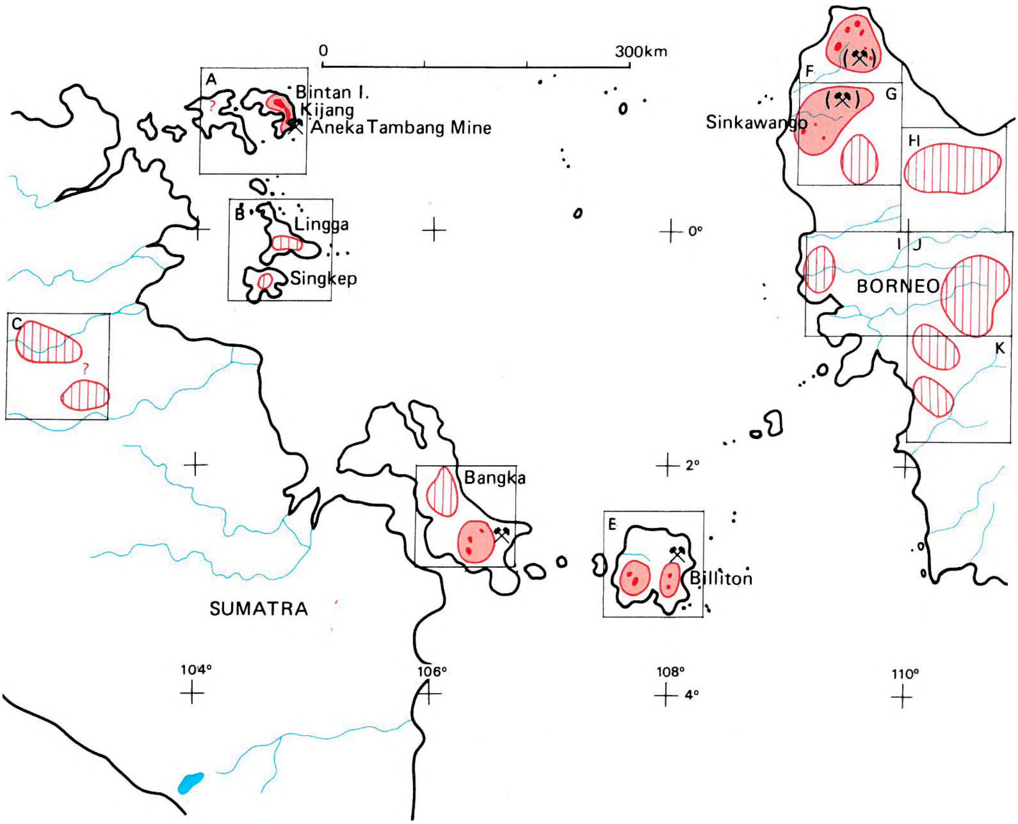


Fig. 44 Indonesia

Source rock: aphanitic hornfels, syenite, phyllite

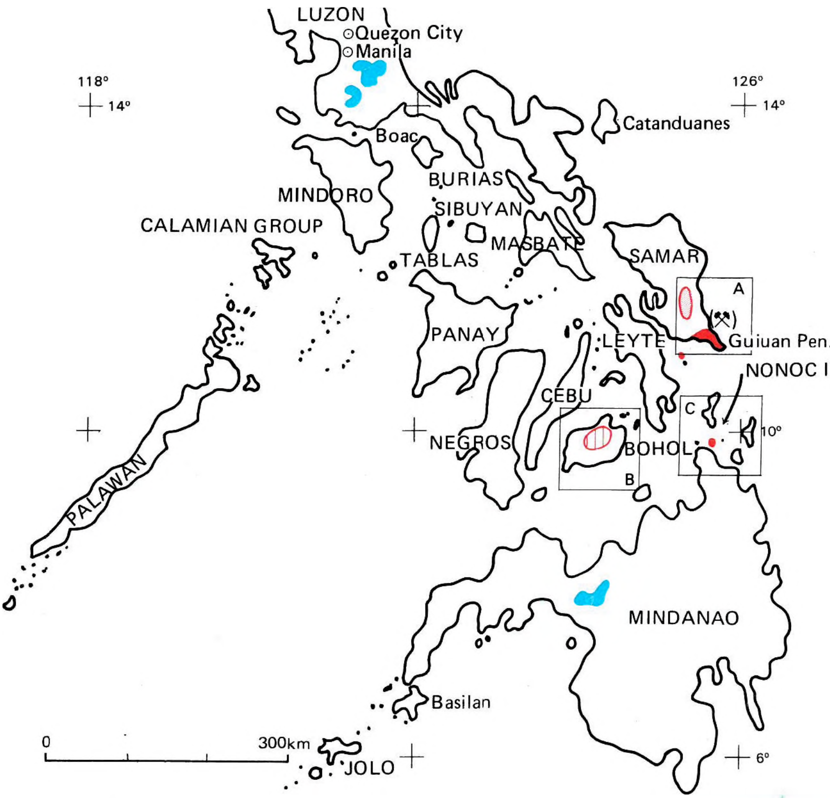


Fig. 45 The Philippine Is.

Source rock: serpentinized dunite, pyroxene peridotite, gabbro

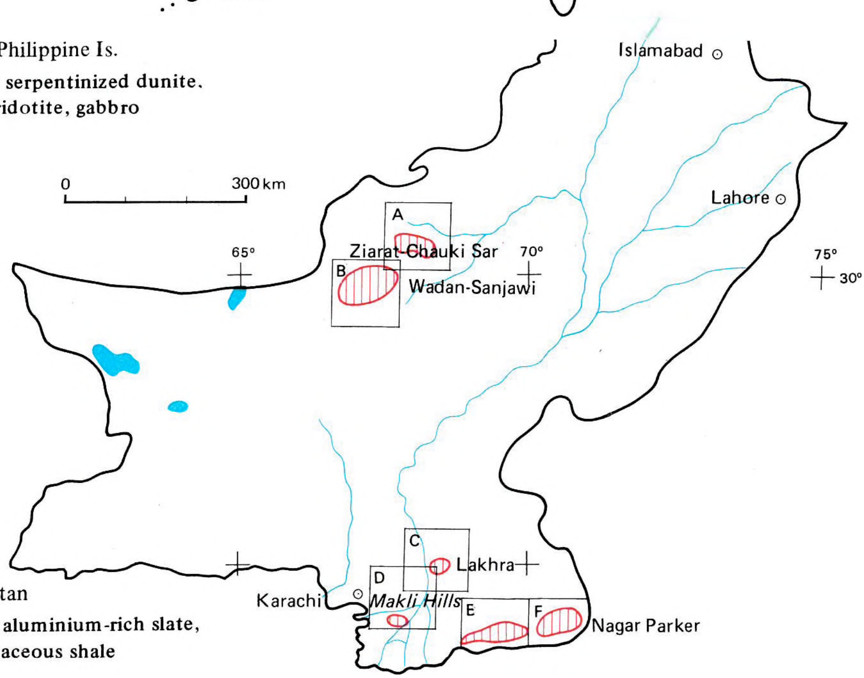
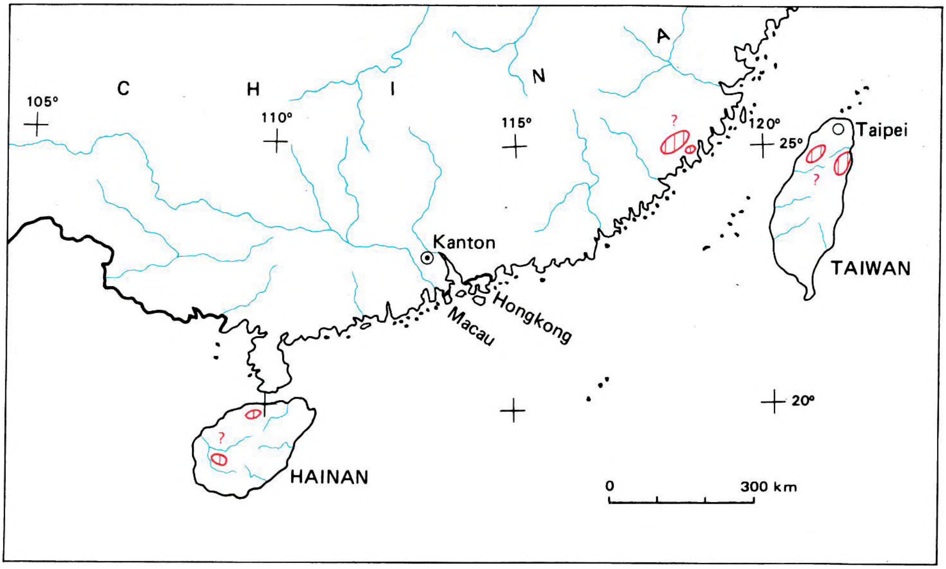
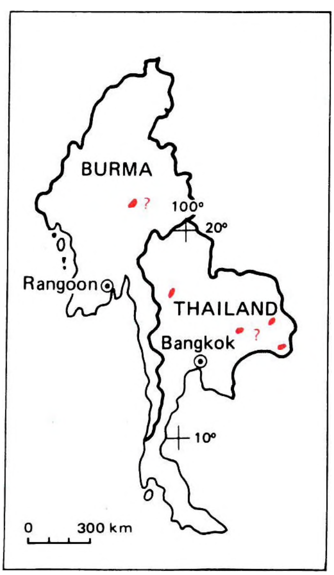
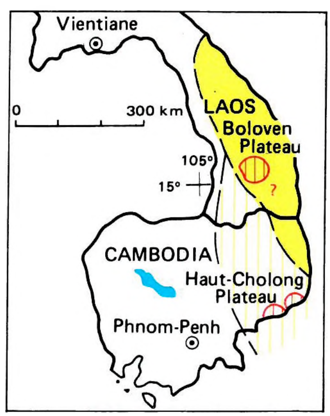


Fig. 46 Pakistan

Source rock: aluminium-rich slate, shale, carbonaceous shale







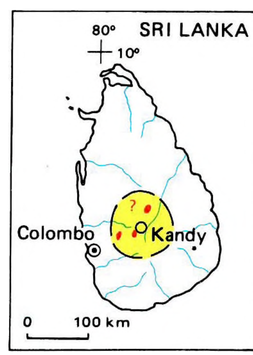


Fig. 47 Asian countries to be taken into account

Source rock: basalt, granite

the harsh road and topographic conditions, the regions of difficult access have so far been avoided by the explorers and the exploration has been concentrated mainly to the coastal belt or to areas close to the sea coasts, access to which has been much more easy. In the jungleclad inland regions (e.g. the interior of Borneo, W Irian) there are traces suggestive of a sizable additional laterite-bauxite potential. The difficulty of access, the lack of an infrastructure, the harsh topography and the unhealthy and, in fact, often not at all safe conditions of living, are no stimuli for exploration in these areas. Long-term reconnaissance programmes, however, may serve the interest of the countries involved, moreover they may awaken the interest of some major aluminium corporations as well. Minor reserves [*Philippines* (Fig. 45), *Pakistan* (Fig. 46)] and traces of bauxite [*Sri Lanka* and *Burma* (Fig. 47)] are known from a number of countries of the continent.

The total potential laterite-bauxite resources of Asia may possibly account for about 20–25% of the Globe's total.

AUSTRALIA

Australia is what may be termed the genuine "bauxite continent" (Fig. 48). Its hitherto identified bauxite reserves exceed 5 thousand million MT, being located, very favourably, on or near the coasts [Weipa, Aurukun, Gove (Fig. 49, 50)] [Mitchell Plateau, Darling Range (Fig. 51, 52)]. For this reason and also because of the favourable power resources available, it is Australia that is taking over the lead in the world's aluminium industry. (In 1983–1987 its annual bauxite production was 24–34 million MT, its

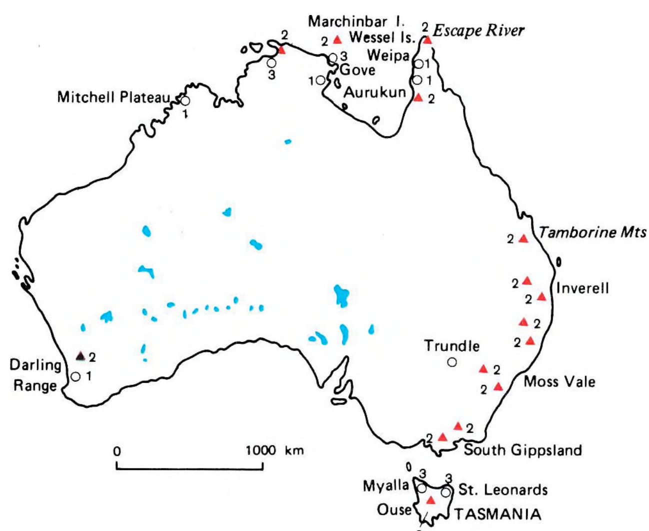


Fig. 48 Australia

Bauxite deposits and regions: (1) with >500 million MT of ore reserves, (2) with 100–500 million MT of ore reserves, (3) with <100 million MT of ore reserves

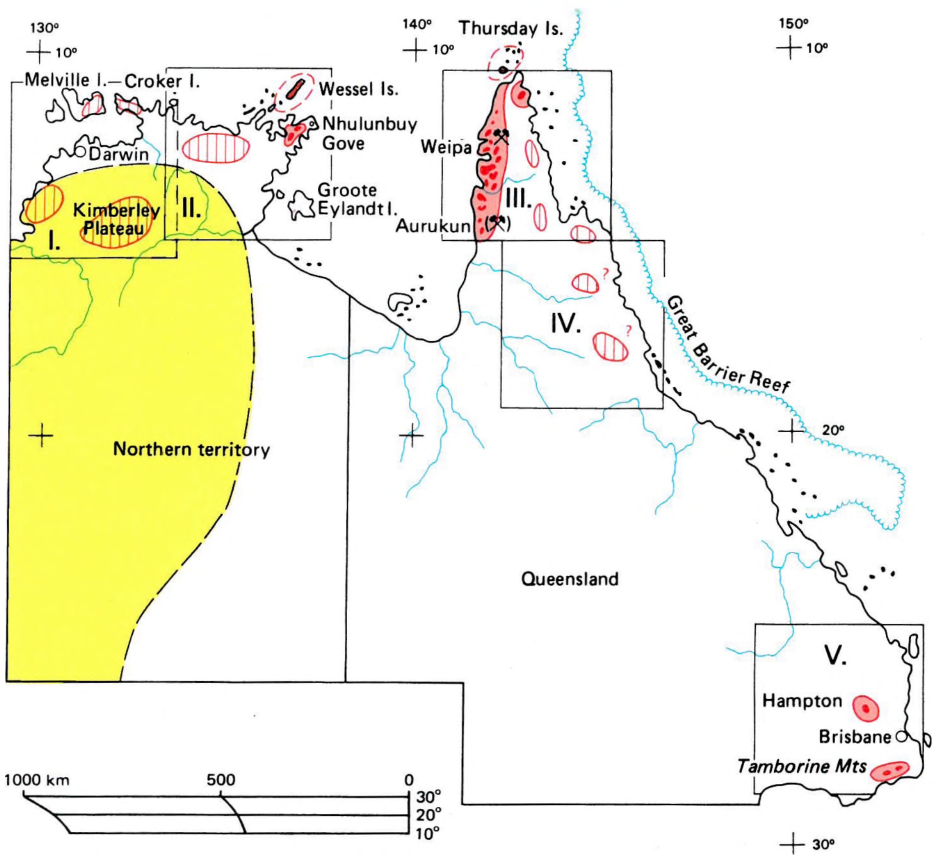


Fig. 49 Queensland, Northern Territory and Hampton

Source rock: arcosic sandstone, granite.—Northern territory: quartzite, sandstone, crystalline schist. Queensland: sandy clay, mudstone, kaolinitic sandstone, granite. Hampton: andesite, basalt

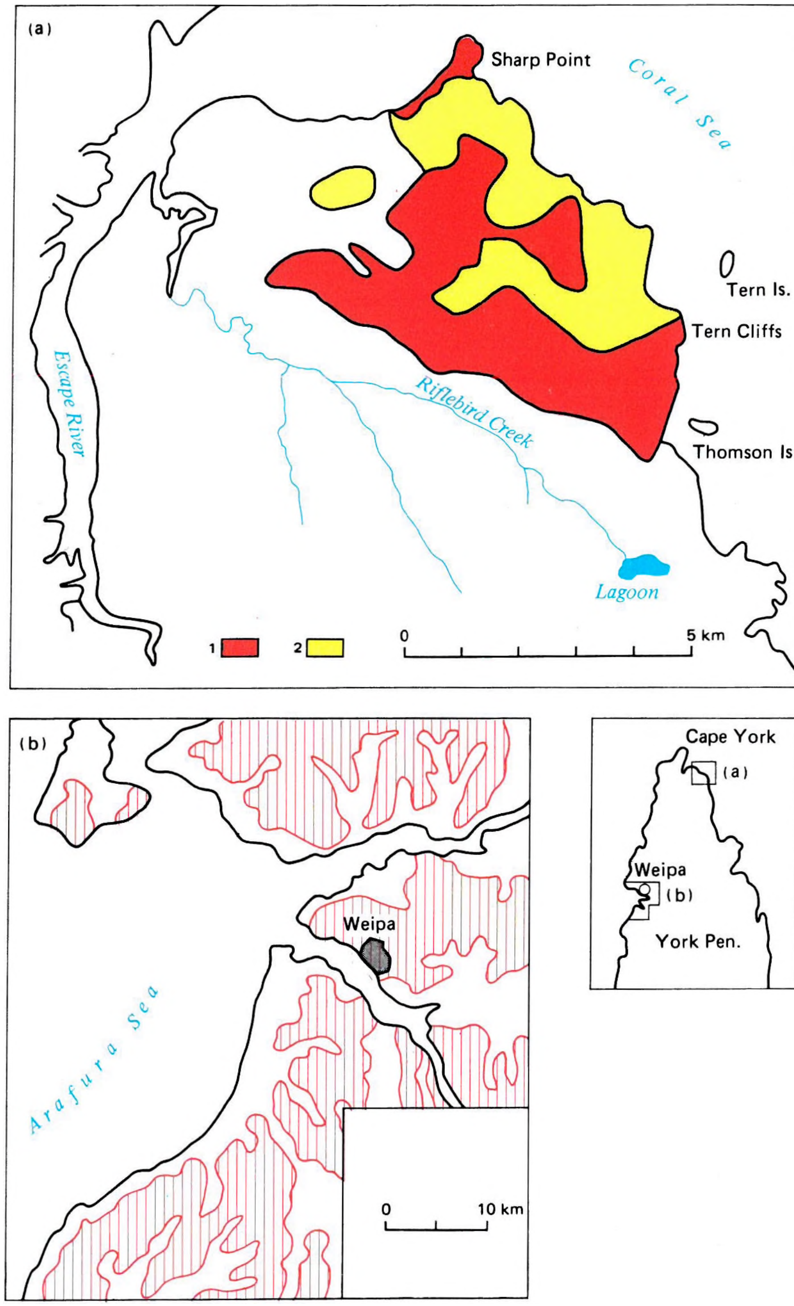


Fig. 50 York Peninsula's laterite bauxite deposits (After A. H. WHITE 1976 and G. DE WEISSE 1964)
(1) Red bauxite, (2) white bauxite

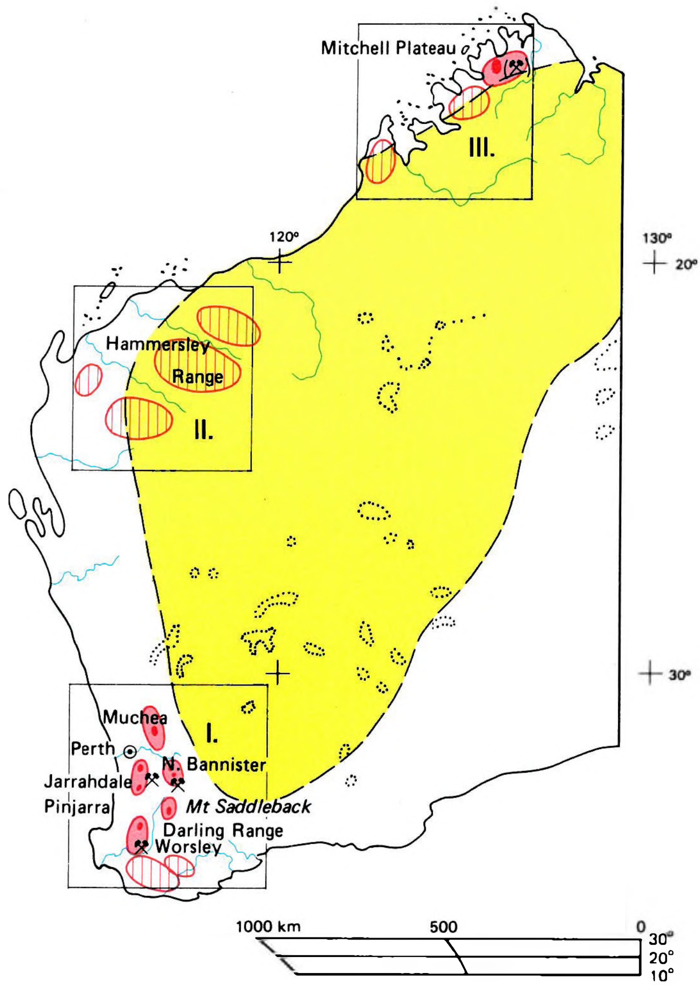


Fig. 51 West Australia

Source rock: granite, quartz dolerite, meta-greenstone, "Carson" basalt, gabbro

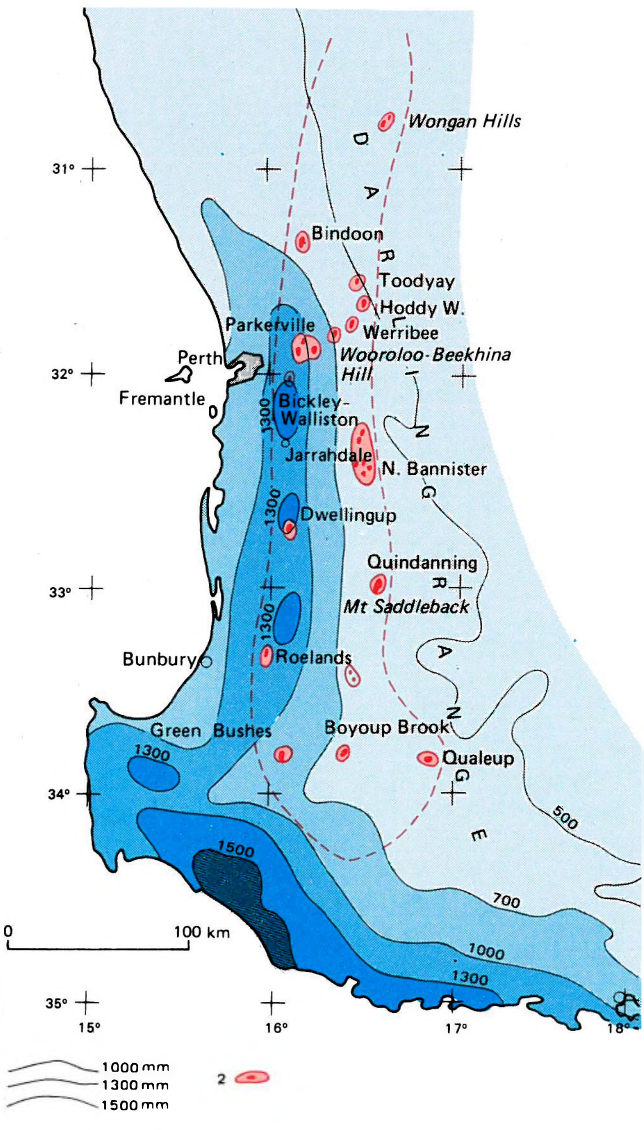


Fig. 52 Bauxite deposits and precipitation conditions in Darling Range (After H. B. OWEN 1954)
(1) Isohyets of annual precipitation, (2) bauxite deposit

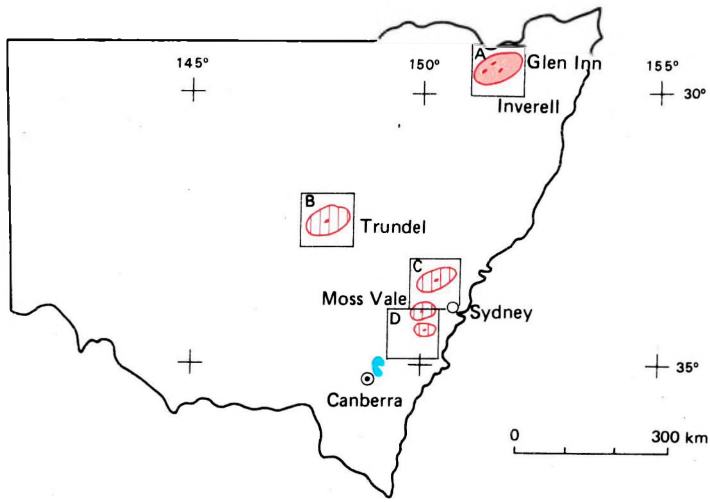


Fig. 53 New South Wales
Source rock: basalt, kaolinitic basalt

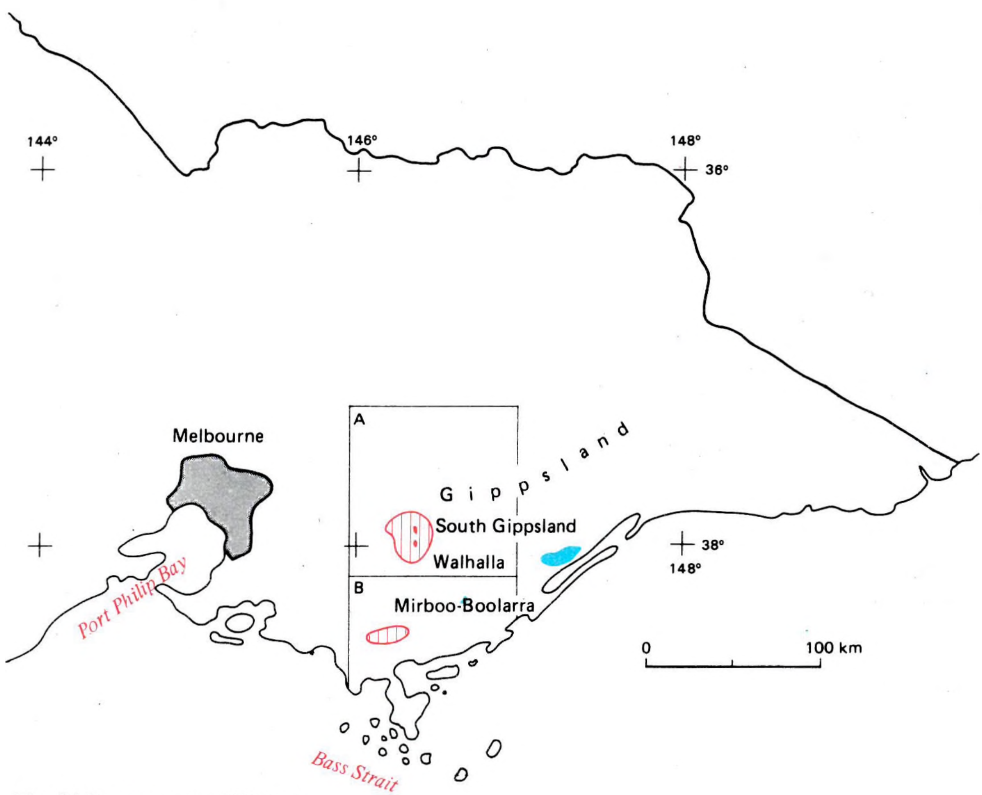


Fig. 54 Eastern part of Victoria
Source rock: basalt

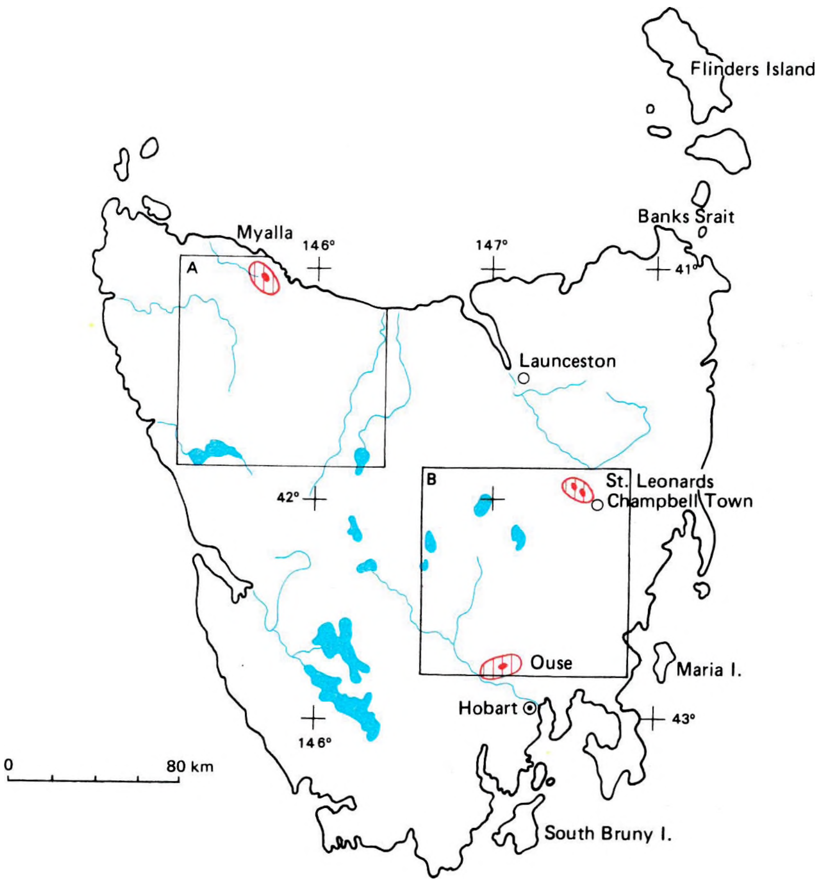


Fig. 55 Tasmania
Source rock: basalt, dolerite

alumina production was 6–10 million MT/year, the annual aluminium metal output of the continent was 1.5–4.0 million MT). New investment projects (opening of a mine, building or extension of an alumina plant and smelter) are being implemented one after the other, mainly by the 6 leading transnational aluminium corporations (ALCOA, ALCAN, REYNOLDS, KAYSER, PECHINEY and ALUSUISSE) as well as joint-venture or, at least partly joint-venture, undertakings with the Australian government (COMALCO).

Although very intensive bauxite exploration projects are in progress, chiefly in areas claimed by some well-known transnational firms (concessions, equity stakes, etc), the areas known to have potential resources, but still poorly covered by detailed exploration or, broadly, totally unexplored, are enormous. The potential laterite-bauxite resources occur, like the already identified reserves, partly on plateaus, partly on platform or peneplain areas of ancient shields. Mainly in the *Northern Territory,* the *N* and *NE of Queensland* and in *West Australia* (Fig. 51) are there vast plateau- or platform-type potential areas that may be regarded as being promising for bauxite discoveries. Comparatively smaller occurrences (deposits) are known from East and Southeast Australia [*New South Wales* (Fig. 53) and *Victoria* (Fig. 54.)], extending as farth south as the South Gippsland and in fact, having an extension even on the island of *Tasmania,* near Ouse, Launceston and St. Leonards (Fig. 55). The presence of bauxite in these last-mentioned areas may even be reckoned with, though these occurrences must be much smaller in volume and of different type as compared to their Mitchell Plateau and Darling Range counterparts.

In Tasmania there is, in fact, little hope to discovering further laterite-bauxite deposits of any considerable size. The potential bauxite resources of Australia may constitute about 15–20% of the Earth's plateau- or peneplain-type laterite-bauxite resources.

OCEANIA

New Zealand

Traces of low-grade bauxite are known and an estimated total of about 20–30 million MT of potential bauxite resources are thus possible in a laterite sequence underlain by basalts near Karikari, NW of Auckland at the northernmost tip of North Island (Fig. 56). A more exact assessment of the potential resources would require to re-in-

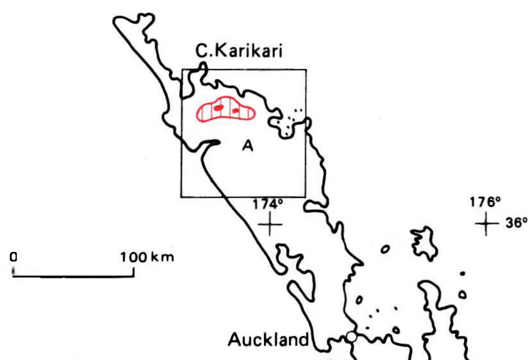


Fig. 56 New Zealand
Source rock: basalt, kaolinitiferous basalt

vestigate the area involved with more scrutiny, but the reserves to be expected do not seem to justify, either in terms of ore grade or in amount, the development of an independent local alumina industry.

Hawaii

On some of the Hawaiian Islands (federal state of the USA) (Hawaii, Kauai, Molokai and Maui), bauxite-bearing, thin gibbsite-laterite and lateritic soil blankets of considerable extension underlain by basalts and basanites sloping at an angle of 5–18°, i.e. slope-laterites, are known to occur (Fig. 57). Of these occurrences, the bulk samples

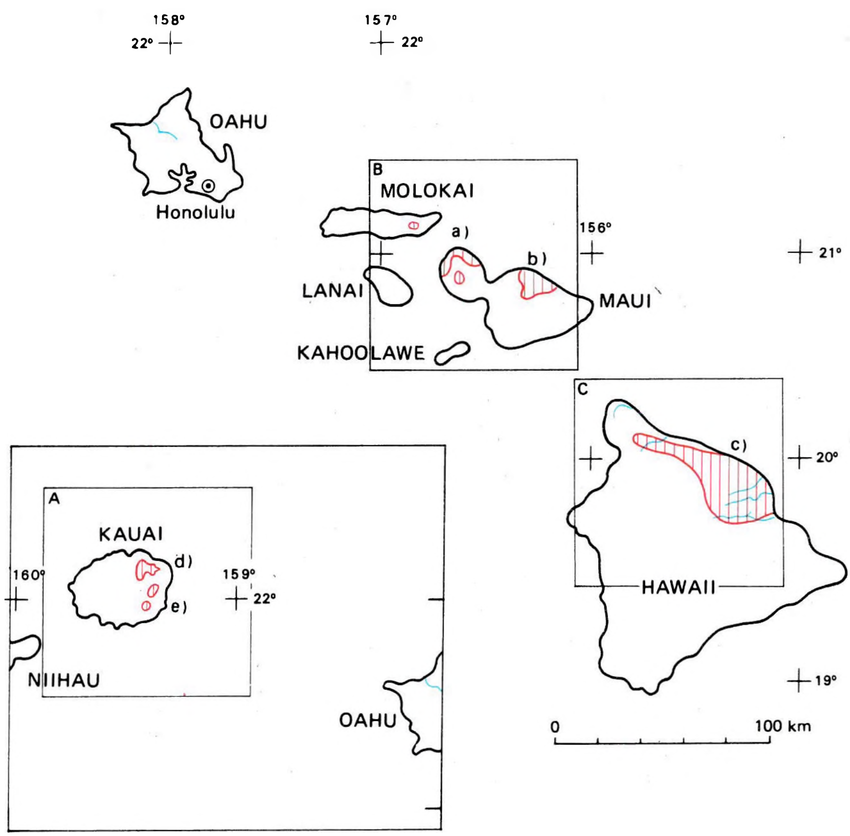


Fig. 57 Hawaii (USA)

Source rock: basalt, basanite: a) Gibbsitic laterite and bauxite, b) gibbsitic laterite, c) gibbsitic laterite and latosol in a thickness of 0–1 m, d) ferruginous, gibbsitic laterite, e) ferruginous laterite and laterite-bauxite from Maui island proved to be the best in grade, though even these correspond only to medium- or low-grade, iron-rich laterite-bauxite. The idea of exploiting them as bauxite was put forward several times, but, from environmental protection, touristic and real estate speculation considerations, it has so far been rejected. On the island of Kauai, the bauxite-bearing gibbsite-laterite is concentrated to a comparatively small area, but on this island, known under the name of "Garden Island", the conservationist and touristic arguments are so strong that, even in case of larger reserves and better ore grade, the launching of bauxite mining development projects would be improbable.

The total potential bauxite resources of the Hawaiian Islands may attain the figure of 200 million MT, and, according to some bold estimates, even 600 million MT. To assess the reserves with more precision would require further, more scrutinized studies.

Republic of the Fiji Islands

Exploration projects launched by Japanese firms have led to discovery of laterite-bauxite occurrences of little importance, though considerable for Oceania, on basalt plateaus in the NW part of Vanua Levu island: discovery upon which a small mine has been based (Fig. 58) to exploit an estimated total of about 23 million MT of bauxite reserves. For economic reasons (ore grade and access to the ore bodies), however, the exploitation was stopped in the 1970's. Minor traces of bauxite are known, in addition,

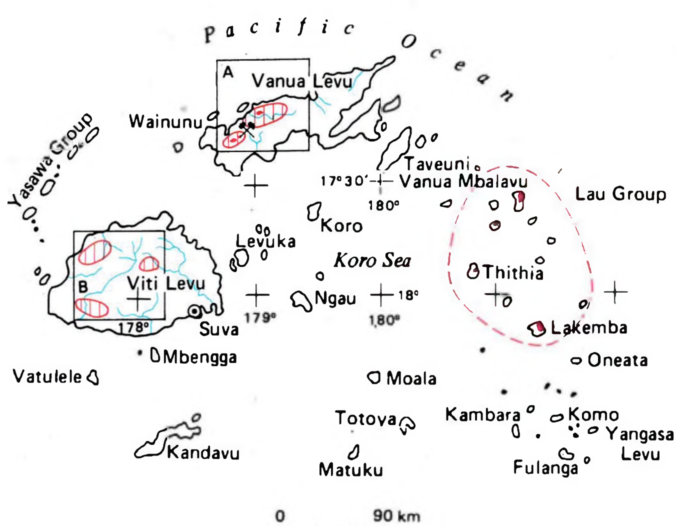


Fig. 58 Republic of the Fiji Islands

Source rock: basalt.—Between 1969 and 1972, it was the Bauxite Fiji Ltd., a Japanese-owned company, that started the exploitation of about 23 million MT of estimated bauxite reserves (including about 8 million MT of bauxite suitable for washing with a 45% recoverable alumina content) of a bauxite deposit of low ore grade at Wainunu on Vanua Levu island. For economic reasons, since 1972, the mining has been suspended.

from the interior of Viti Levu and from several islands of the Lau group. Neither from the point of view of ore grade, nor from that of quantity do the potential resources seem to meet the requirements of developing a local aluminium industry. A more realistic assessment of the potential resources would require the revision of the exploration results available.

Other traces of laterite-bauxite or very modest laterite-bauxite reserves are known —as a result of exploration carried out so far—from several islands of Oceania such as Ponape, Guam, Mariana Is. Babelthuap (Palau Is.), Truk Is. (Moen I.), Manus (Admiralty Is.), Vanikoro (New Hebrides: Republic of Vanua Atu), but these are commercially insignificant (Fig. 59).

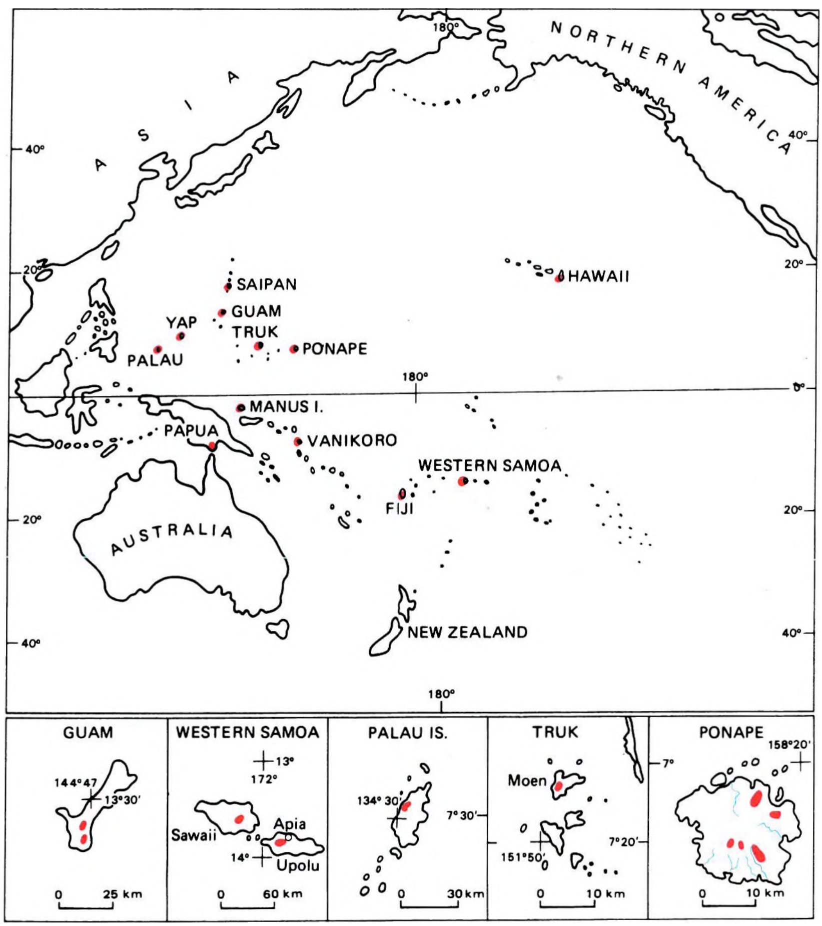


Fig. 59 Other countries of Oceania to be taken into account

METHODOLOGY

1. COMPUTER APPLICATIONS FOR THE FORECAST METHOD

To determine the reliable amount and average grade of plateau- and peneplain-type laterite-bauxites within a particular deposit is one of the most difficult tasks of exploration and evaluation. In most cases it is the difficulties involved in determining the optimum borehole (and/or pit) spacing aimed at increasing the borehole (and/or pit) density owing to the extremely unsteady variation (sometimes even at decimeter intervals) of the ore grade (Al_2O_3, SiO_2 and Fe_2O_3 contents) rather than the difficulties of drilling (or pitting) in an environment of rough topography that pose the problem. To find blocks, clastics and breccias of varying size consisting of laterite and bauxite enclosed in a softer argillaceous matrix is a quite frequent and, in fact, overall phenomenon. This matrix may be, for that matter, of red clay character or it may happen to represent a product of weathering of low-bauxite-grade clay character. The ore grade within a sequence is monitored by the borehole (or pit) in dependence on the cross-section or the proportion in which the lateritic-bauxitic material of breccious texture with heterogeneous clasts has been assessed by the sampling and on the local ratio of the bauxitic material to the nonbauxitic one (allite–siallite–ferrallite–fersiallite portions) within the profile sampled in one particular case or in another, the locally not at all insignificant, half-weathered or completely unweathered source rock debris not being left out of the account. Since the variation in ore grade is extremely unsteady, depending on the clasticity of the source rock, the porosity and a lot of other local factors, there is no guarantee for determining the zone of influence to which the analyses from the boreholes may be extrapolated. This is why the reduction of the borehole (and/or pit) spacing in the grid to some extent or other may fail to enable the determination of the average ore grade within a deposit, for the new analyses resulting from concentration of the borehole (and/or pit) grid will scatter to the extent that the size of the scatter will largely exceed the figure that has been obtained from the earlier, more widely spaced borehole (and/or pit) grid. Very seldom will it be possible to reach, by concentration of the boreholes (and/or pits) that limit, the still economical optimum, at which the changes in ore grade will become standard ones, i.e. where the changes in ore grade resulting from further concentration will be negligible.

Hence the recent use of the so-called "bulk-sample" method for the technological testing of the explored laterite-bauxite deposits, an approach using the largest possible representative sample (several tons) which is supposed to represent the average ore grade to be expected during exploration. Of course, there are relatively homogeneous ore deposits of good quality, different from the ones just discussed, being, as a rule, very old. These are mentioned only because, in practice, these are that which reflect best of what is meant when the average ore grade of a laterite-bauxite deposit (ore body) is being spoken of. Distinction must be made between the average ore grade of a deposit calculated on the basis of the exploration results and the average ore grade of a "bulk-sample" and the average ore grade verified in the course of exploitation of the deposit.

How is it possible then to give a forecast acceptable for the practice in spite of such a variability, a forecast of the ore grade and the reserves of bauxite deposits that are still unexplored or very poorly explored and maybe just supposed?

Before answering the question, let us point out first of all that there exist favourable hydro-geomorphological conditions for the assessment and prediction of plateau-type laterite-bauxites, conditions quite frequently encountered. Using the so-called *circular profiling method,* the type of the water (balance) regime, its character, the section portions or intervals on the way of lateritization and bauxitization can be inferred, with very high probability, from the topographic map of proper scale of a particular laterite plateau. From these data, the average bauxite thickness values and surface areas (the apparent wet specific density, bulk density, being selected) can be calculated and determined; consequently, the reserves can be assessed. The factor-equivalents calculated for the average chemical composition of the source rock (Al_2O_3 and SiO_2 being interesting) and for the main genetic factors can be used for determining the average laterite-bauxite ore grade to be expected. The reserves thus calculated with the first approximation and *their average ore grade, the first grade,* will very seldom correspond to an acceptable average ore grade coming close to the reality in the case of the plateau involved in the forecast: further precision, refinements, need to be added.

In countries or major bauxite areas, where the average ore grade of several bauxite plateaus is already known with satisfactory precision from earlier exploration results (should it be from final reports of detailed exploration, should it be with data confirmed by mining results), one can proceed to carrying out that comparative analogy test using more than 40 different correlation diagrams from which, in case of correlatability, by studying the correlations of some parameters (in case of the presence of a proper number of ore bodies), the *trends* can be inferred. The identification of these trends is extremely important for adding further precision to the rough ore grade assessment that has been reached with the first approximation. *The know-how of adding precision to the first estimate is the subject of an expert's work and is patented.*

The *second ore grade* calculation can be developed from the first estimate by using the identified trends with proper transformation corrections. The magnitude of the modification depends on the nature and type of the trends and the correlatable parameters. The resulting *third ore grade* is still eligible to further refinement. Namely, the third grade already comprises the results of environmental analogy-tests aimed at adding further precision, the prospective best-quality bauxite plateaus or plateau-portions being selected on the basis of the identified trends. It is in the light of the results of the *strategic or orientation* boreholes to be located at optimum-points proposed by the expert (results that may possibly modify the results hitherto available) that the final corrected qualitative-quantitative calculation of the predictive reserves can be carried out which will, at the same time, give the final result of the whole forecast survey *(the fourth grade).* These steps are proposed to be used in computer applications.

Conclusion

The new complex forecast method can be used both by manual calculation and enhanced by computer. Even in developing countries, in desolate regions with no access to electric power mains, it is possible to perform this kind of computer-enhanced calculation. Nota bene, there is a wide choice of individual computer types which are eligible to performing the task excellently and quickly, provided that the necessary basic data are available. When working on the field, even a mobile-home-based computer centre would suit the purpose.

To have the method adapted to being fed into the computer, after carrying out a *manually-performed series of measurements-calculations,* the bauxite-explorers will have to develop a proper *software* well adapted to the parameters of the country or area involved.

First of all, the method will have to be tested in a well-known, explored bauxite area readily characterizable by data (e.g. some regions of India, Australia, Brazil, Suriname, Ghana, Guinea, etc). Next to follow will be to test the "software" adapted to the concrete values, in the same areas. During the survey there will certainly be need for some further minor improvements. In bringing the computer-enhanced system on stream, it will be possible to extend the survey gradually to less and less known and, finally, to totally unknown plateaus as well as to laterite plateaus that may be rated as promising. The lead-times required for testing the survey system, its programming and providing with software may take some 6–12 months.

A chain pattern-draft on developing the computer-enhanced system is given under the next heading. Next to follow the minimum in hardware configuration needed for the calculations will be described in a seprarate chapter (Fig. 60).

In Figures 61–63 the conditions of laterite-bauxite forecast (Fig. 61), the levels of resolution involved (Fig. 62) and the levels of application of the selection of prospective areas (Fig. 63) are shown.

Hardware configuration needed for running the system. Minimally needed units of the system: 1 piece of personal computer, 1 piece of floppy disk unit and 1 piece of matrix printer.

The feeding of the data into the computer system is done by typing on the keyboard. The basic data, the intermediate results of computation, the functions needed for it and the programs themselves can be stored in the floppy disk unit. The results of computation and analyses can be printed on the matrix printer.

Fig. 61 Continued

GROUP	FACTORS	CANCELLING CONDITIONS	OPTIMUM CONDITIONS
MORPHOLOGICAL	Plateaus of medium size	<1 km^2	1–10 km^2
	Large plateaus	<10 km^2	>10 km^2
	Perimetry index $\frac{\text{T km}^2}{\text{K km}}$	if <0.8	1.5–5.0
HYDROGEOLOGICAL	Percentage of completely water-saturated zone as referred to the total of the sequence	$>75\%$	$<25\%$
	Percentage of the periodically water-saturated zone as referred to the laterite sequence		$>25\%$
	Percentage of the completely dry zone as referred to the laterite sequence		$>50\%$
	Rate of flow of rainwater percolating through the laterite sequence	>3 m/minute	0.2–1.0 m/minute
	Depths of the groundwater table as referred to the plateau-top	>100 m	10–50 m
	Permanent water outputs (springs, rivulets)	300 m deeper as compared to plateau-top level	by about 20–50 m lower as compared to the plateau-top level
pH	pH conditions in surface marshes	<4 and >9	between 4.5 and 8 pH
	Water temperature	$<10°$C	22°–29°C
BIOLOGICAL	Coverage by vegetation: dense tropical forest	swamp or marsh forest	50–75% of the plateau- top
	Wooded, bushy savannah		50–100% of the plateau-top, locally with termite structures
	Total lack of vegetation	90–100%	
	Total lack of soil cover	90–100%	

Fig. 62 **Levels of resolution and assessment of computer-enhanced laterite-bauxite forecast**

Definition:	Level	
Based on known deposits and their geohistorical and present-day geographical conditions	Lateritebauxite zone	Zones 1–7
Classification of laterite-bauxite areas according to their political status and the national boundaries	Country, area	About 20 important and about 20 recommended (promising) countries + other countries to be taken into account (about 30)
Selecting of areas and topo-morphologies meeting the conditions for laterite-bauxitization within the area of individual countries by means of computer, using square grids of 500x500, 100x100, 10x10 and 1x1 km	Bauxite deposit, region, plateau area	In numbers varying by countries (1–10)
	Plateau group, plateau range	In numbers varying by countries in dependence on geographic situation and morphology
Computer-enhanced analogy method including studies of correlation with known deposits in the surroundings, finding out and using trends and conversion coefficients (factor equivalents)	Plateau complex	Depending on topo-morphology
	Plateau (individual)	Depending on topo-morphological factors
	Sub-plateau	(top, tongue, neck, slope, escarpment, edge, depression, marshes, bench, ridge, extension of ridge)
Optimization drilling and pitting and improvement of and adding further precision to earlier calculations by using the optimization results. Synthesis: for separate plateaus and deposits and, subsequently, a nation-wide synthesis		Depending on plateau-morphological factors

Fig. 63

Chain patterns of selecting areas within plateaus that are

A) Laterite-bauxite zone
(classification, proposed by GY. BÁRDOSSY, São Paolo, 1982)

B1 Countries*
(Within laterite-bauxite-zone)

A1 West Africa	A2 West and North Australia	A3 Southeast Asia
Republic of Guinea**	West Australia**	China (S part)
Republic of Guinea-Bissau*	Northern Territory**	Taiwan
Republic of Sierra Leone*	Queensland**	Vietnam**
Republic of Mali*		Laos
Liberia		Cambodia
The Ivory Coast		Thailand
Ghana*		Malaysia*
Republic of Togo		Indonesia*
Bourkina Faso		Philippine Is.
Chad		
Niger		
Benin (Dahomey)		
Nigeria		
(Gambia)		
(Senegal)		
(Central African Republic)		
(PDR Congo)		
Cameroon		

A8

B2 Countries and other territories
(Without the laterite-bauxite zones)

in Oceania	in South America
New Zealand	Brazil* (Central and Southern parts)
Republic of the Fiji Is.	Colombia* (W and E parts)
Papua New Guinea	Paraguay
Solomon Is.	Ecuador
Western Samoa	Bolivia
Vanuaaku (New Hebrides)	Peru
New Caledonia	Argentina (Misiones)
Guam I.	
Ponape I.	
Yap Is.	
Palau Is.	
Truk Is.	
Saipan I.	
Vanikoro I.	
Manus I.	
Hawaii Is.	

* In countries marked with an asterisk a total of >100 million MT of proved plateau-type laterite-bauxite reserves (1987)

promising for laterite-bauxite.–Level of application

A4
The Guyana Shield

Brazilia** (N part)
Venezuela**
Federal Republic of Guyana*
Suriname*
French Guyana
Colombia (E part)

A5
India

Saurashtra*
Maharashtra
Kerala
Madra Pradesh
Andhra Pradesh*
Madhya Pradesh*
Orissa**
Bihar*
Uttar Pradesh*
Goa*
Srí Lanka (Ceylon)

A6
Southeast Africa

Malgache Republic*
Republic of Mozambique
Republic of Malawi
Republic of Zimbabwe
Swaziland
Republic of the Seychelles Islands

A7
Southeast Australia

New South Wales
Victoria
Tasmania

Others

in Asia

Pakistan
Nepal
Bhutan
Burma

in Africa

Zaire
Gabon
Equatorial Guinea
Angola
Zambia
Uganda
Sudan (S part)
Kenya
Tanzania
Ethiopia
Rwanda
Burundi
Republic of South Africa
Comores Is.

in Central America

Costa Rica*
Panama
Salvador
Honduras
Nicaragua
Belize
Guatemala
Mexico (S part)
Cuba (Oriente)
Dominica (Rouseau)
Puerto Rico

** >1000 million MT of proved laterite-bauxite reserves

2. HYDRO-GEOMORPHOLOGICAL METHOD OF EVALUATION FOR PRELIMINARY ASSESSMENT OF THE POTENTIAL RESOURCES OF PLATEAU-TYPE LATERITE-BAUXITES. (SUBSYSTEM OF THE COMPLEX METHOD.)

PRINCIPLE AND PRACTICAL USE OF THE METHOD

As shown by practical experience, the water (balance) regime of plateau-type laterites or, as referred to under a different name, groundwater laterites, or laterite-bauxites derived from them varies, as far as the behaviour of the infiltrating precipitation is concerned, primarily in depencence on the position of the underclay, a transitional, impermeable layer referred to as saprolite (lithomarl) under the laterite sequence, and on the thickness and surface morphology of the laterite sequence overlying it as a cap. Adapted to such geological-morphological circumstances, the water regime (in the case when proper climatic and geohistorical prerequisites are granted) is a controlling factor crucial for the leaching and removal of the SiO_2 contained in the laterite sequence, thus being essentially responsible for laterite-bauxitization. By reconstructing it from a particular profile or from another, conclusions as to the thickness and ore grade of the bauxite supposed to have developed within the profile can be drawn.

By relying on the afore-mentioned facts based on experience and on his own observations (in West Africa, Southeast Asia and Central America), the author developed a method which enables one to determine, quite efficiently and easily, the hydro- and geomorphological conditions crucial for the formation and preservation of laterite-bauxite on a particular plateau studied, a part of a plateau or, for that matter, a plateau complex of more intricate ground plan configuration and, to some extent, even for the development of peneplain-type laterite occurrences. [Horizon(s) of laterization.]

The availability of hydromorphological and geomorphological characteristics favourable for laterite-bauxitization can be determined very simply from the circular profile of a plateau. The documentation to start with in doing so includes:

1 The detailed topographic map of the prospective plateau to study. A map on a scale of at least 1:50 000 or, if possible, one of even larger scale, 1:25 000 or 1:10 000, is needed. In case of topographic maps of smaller scale (e.g. 1:62 500 or 1:100 000) the resolution of the basic contour lines as a rule does not attain the magnitude needed for determining the availability of the afore-mentioned prerequisites in a sufficient detail.

2 The topographic contour line map to be used must carry a reliable hydrography. Consequently, the sites of permanent water springs must be shown reliably on it.

3 Are the forest areas represented and the forest boundary given on the map, so this will largely enhance the interpretation.

4 Let us list the *basic data* concerning the areas (plateaus) to be assessed the availability of which is desirable:

- the mean annual amount of precipitation (a long-term average or an estimate of good approximation);
- the average precipitation of the wet and the dry seasons (measured long-term average or an estimate of good approximation);
- the mean annual temperature in °C (measured or estimated);
- the mean annual temperatures of the wet and dry seasons (actually measured or estimated);
- the rock constituting the plateau and its geological age, average chemical composition as referred to fresh source rock;
- the average altitude a.s.l. of the plateau surface or peneplain and the average altitude of the denudation level to which the plateau is assignable and the geological age of the denudation level (e.g. Gondwana, post-Gondwana, etc).

The use of graphic representation (plotting) techniques will enable the user of this method to derive, from the afore-listed initial documentation and data, a wealth of information (estimated average thickness of the laterite sequence, groundwater flow directions, thickness and ore grade of the bauxite to be expected). On the basis of these pieces of information, estimates can be made as to the amount of the laterite-bauxite resources to be expected within the subplateau, plateau or plateau-complex deemed to be prospective, moreover, even as to its tentative ore grade and the position of the ore body (bodies) within the profile. Naturally, the inferred and calculated potential quantitative and qualitative data of the bauxite resources to be obtained by the method are on the level of a preliminary estimate, which holds particularly true of the ore grade data. Thus no exorbitant requirements as to their reliability are to be claimed.

As proved by *evaluating control measurements* of known occurrences of different type and structure (Fig. 64), the method, when based on well-founded and reliable basic documentation, has given surprisingly good results (within standard deviation of ±30%) that are more precise and accurate than any of the preliminary estimates of prospective (hypothetical and speculative) resources ever made could provide. As regards the quality of the resources estimated by the new method, the reliability is again higher as compared to the earlier estimates, for, judging by the experience thus far available, the method based on the joint consideration of both the water regime characteristics and the morphology gives results of higher probability. This is well reflected by the plotted circular profiles of plateaus, since here the groundwater table morphology, the "dry zone(s)" the water flow rates, the thickness of the laterite sequence and the supposed geological features of the bauxite sequence to be expected, in a mutually overlapping position as they occasionally are, may be checked immediately in the profile: work easy to perform during one overall survey.

The method has the advantage of being based on relatively realistic geological and morphological evidence, of constructing the most probable model of the reality using a circular profiling of the plateau and of not being labour intensive. Using simple graphic representation, plotting, techniques, it provides, as compared to the earlier methods, a higher level of efficiency and reliability, in assessing the quantity and quality

The new hydro-geomorphological method has been used, as a control, for the assessment of the following laterite-bauxite plateaus

New method			No.	Conventional method	
Country	million MT	%		Locality	million MT
Ghana	1.01	115	(1)	Mt Ejuanema	1.16
	101.60	115	(2)	Kibi-Atewa-Range	88.30
India	22.10	96	(3)	Gudem Block IV.	23.20
	156.80	90	(4)	Panchpatmali-C.	173.10
	170.00	87	(5)	Baphalimali	195.70
	26.20	92	(6)	Chittamgondi	28.50
Suriname	24.50	122	(7)	Nassau Mts	~20.00
	53.00	118	(8)	Lely Mts	~45.00

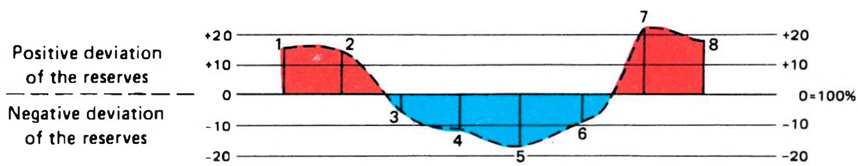


Fig. 64 Deviation from the conventional method in %

of the potential bauxite resources to be expected. To determine the potential resources of a particular plateau complex will take merely a couple of hours time even in case of manual plotting and calculation. Inasmuch as the method can be fed into computer, the time required for the work will be substantially reduced.

Steps of computation: phases of work by the method

Experimental example for the use of the method:

1 The selection of the plateau(s). Select the plateau to be examined concretely for potential laterite-bauxite resources by relying on the system of criteria stipulated (Fig. 65).

2 The plotting of a circular profile. Take the topographic contour line map of proper scale of the plateau (M=1:50 000–1:10 000) in order to determine from it the points of emergence to the surface of permanent water flows (rivulets, springs, etc) and their altitude points (points 1–11 in Fig. 65). Connect these by (imaginary) straight lines and thus plot them on proper scale (if necessary and justified, with exaggeration of the vertical scale) in form of a circular profile so as to return, on the side of the particular individual plateau, from point 1, through points 2, 3 . . . , to the starting point. Such an approach will lead to locating the upper reaches, characterized by the upwelling of springs, of the planimetric layout of the circular profile of the plateau, provided that, in addition, the positions of the altitude points projected into the diagram and representing the margin of the plateau surface are assessed in the background of the individual points. It is that part of the profile between two rows of points of different altitude that gives,

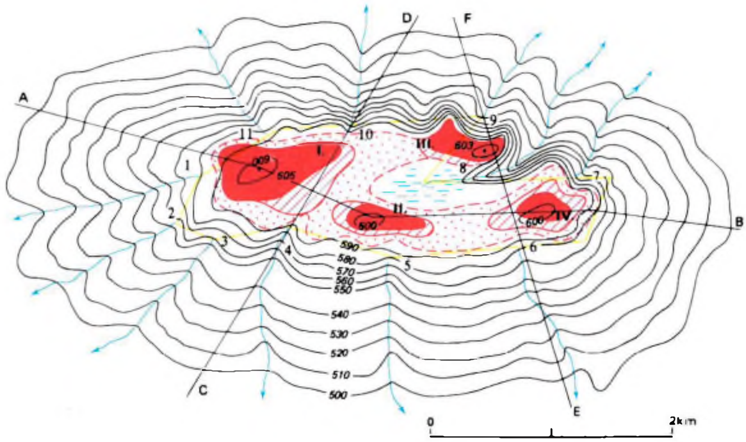


Fig. 65 Idealized sketch map

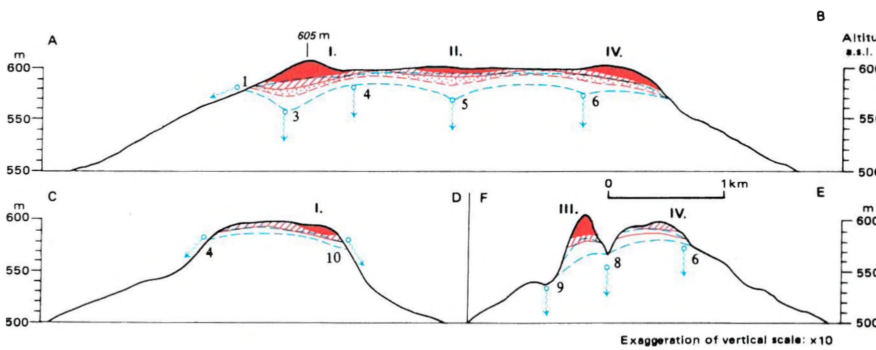


Fig. 66 Idealized sketch profiles

schematically, the profile thickness between the (high) groundwater table and the margin, characteristic of the plateau, i.e. the interval within which the laterite sequence (and the bauxite in it, if any) and the overlying beds of varying thickness are situated (soil, etc). Plot upon this profile altitude point-row, in form of dots or dashline, the dot-row of the altitudinal axis of the plateau which gives further information on the relationship between the water regime of the plateau and the laterite sequence (Fig. 66).

3 Looking at the resulting *"circular plateau water balance profile"* converted into a planimetric configuration (Fig. 69), you can read off information on the profile segments of difference in surface topography and water table, where the conditions for percolation through the sequence, for the leaching of silica, for lateritization and, in this context, for possible bauxitization are most favourable. By analogy with practical experience and consideration of thickness proportions in these profile segments, you can locate the zones of most probable bauxitization, and projecting these back to the

Fig. 67a

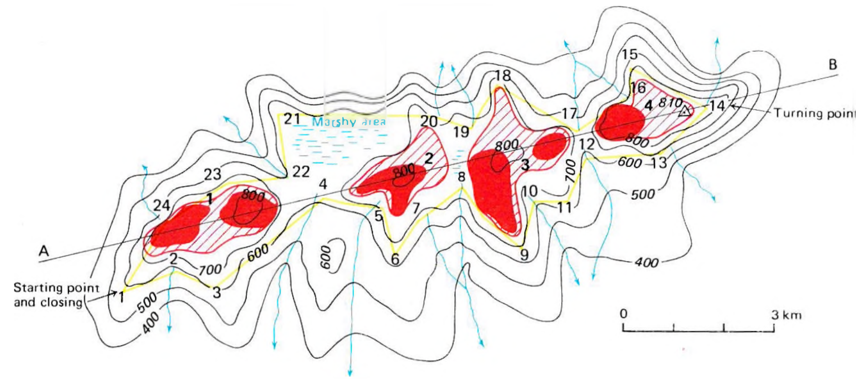


Fig. 67b

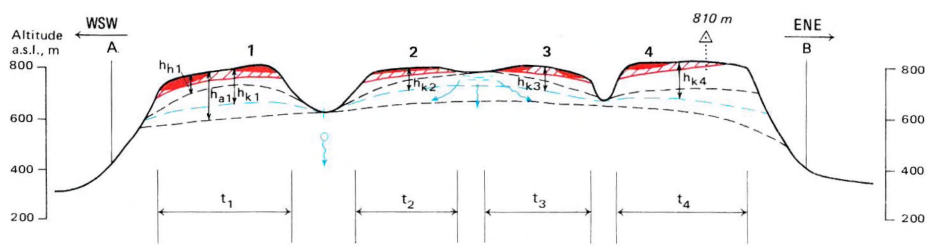


Fig. 67c

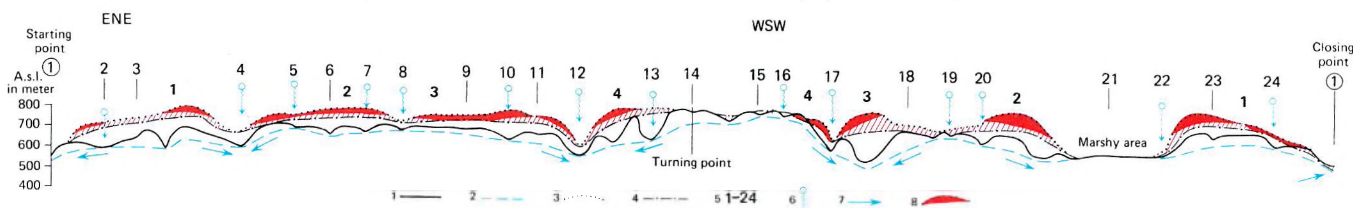


Fig. 67 Idealized sketches illustrating the method of "circular-profiling" of a laterite-bauxite plateau and the technique of modelling its expectable bauxite tonnage

map, you can locate the presumably bauxitized spots and their area. Looking at the profile, you will then be able to estimate the average thickness of these bodies. Multiplying the total of the "bauxite" areas inferred from the topographic map by the average bauxite thickness inferred from the profiles, with due regard for the probable apparent wet specific density [$(MT/m^3) = t$] that may occasionally be included in the calculation, you will obtain, by simple multiplication, the probable bauxite resources of the plateau (Fig. 65 and 67) (e.g. blocks I–II–III and IV and blocks 1, 2, 3 and 4).

Calculation of the bauxite reserves to be expected:

$$a \times b \times t = P,$$

where a = area in m^2 (or km^2)
b = average bauxite thickness in meters (as inferred from the profiles)
t = apparent (wet) bulk specific density (MT/m^3)
P = potential reserves in MT (or millions of MT)

(for an example, see Fig. 65, as calculated for Blocks I + II + III + IV).

Abbreviations, signs and their meaning

t_1 = area of plateau deposit No. 1 in square metres
t_2 = area of plateau deposit No. 2 in square metres
t_3 = area of plateau deposit No. 3 in square metres
t_4 = area of plateau deposit No. 4 in square metres

$t=t_1+t_2+t_3+t_4$=total area of plateau deposits Nos 1, 2, 3 and 4 on the basis of hydromorphological "circle-profiling"

$h_{k_1}, h_{k_2}, h_{k_3}, h_{k_4}$ = depths of the medium groundwater level of the plateau as measured from the surface in metres, related to $t_1 - t_4$

$$h_{k_1} = \frac{h_{h_1} - h_{a_1}}{2}$$

where: h_{h_1} =average groundwater level of the plateau in the wet (humid) season,
h_{a_1} =average groundwater level of the plateau in the dry (arid) season.

$h_k = \frac{h_{k_1}+h_{k_2}+h_{k_3}+h_{k_4}}{4}$ average arithmetic mean of hydromorphologically modelled medium groundwater levels of the plateau.

Formula of expectable bauxite reserves: $\Sigma BxMt = t \times \frac{h_k}{(3)-(5)} \times 1.6-1.7$

*To show the setting of bauxite/laterite formation, *Figs. 67b–c,* the uppermost parts of the section and "circle-profile" have been vertically more exaggerated as their compared to the respective vertical scales.

Legend of "circle-profile" (Fig. 67c)

(1) Topography of the "circle-profile", (2) modelled groundwater table (mean annual) of the "circle-profile", (3) back ground topography of the plateau-top, projected into the "circle-profile", (4) modelled groundwater table of the background-topography of the plateau-top, projected into the "circle-profile", (5) broken points of the "circle-profile", (6) water sources in the "circle-profile", (7) main directions of groundwater-flow in the "circle-profile", (8) supposed bauxitized and/or laterized parts of the profile

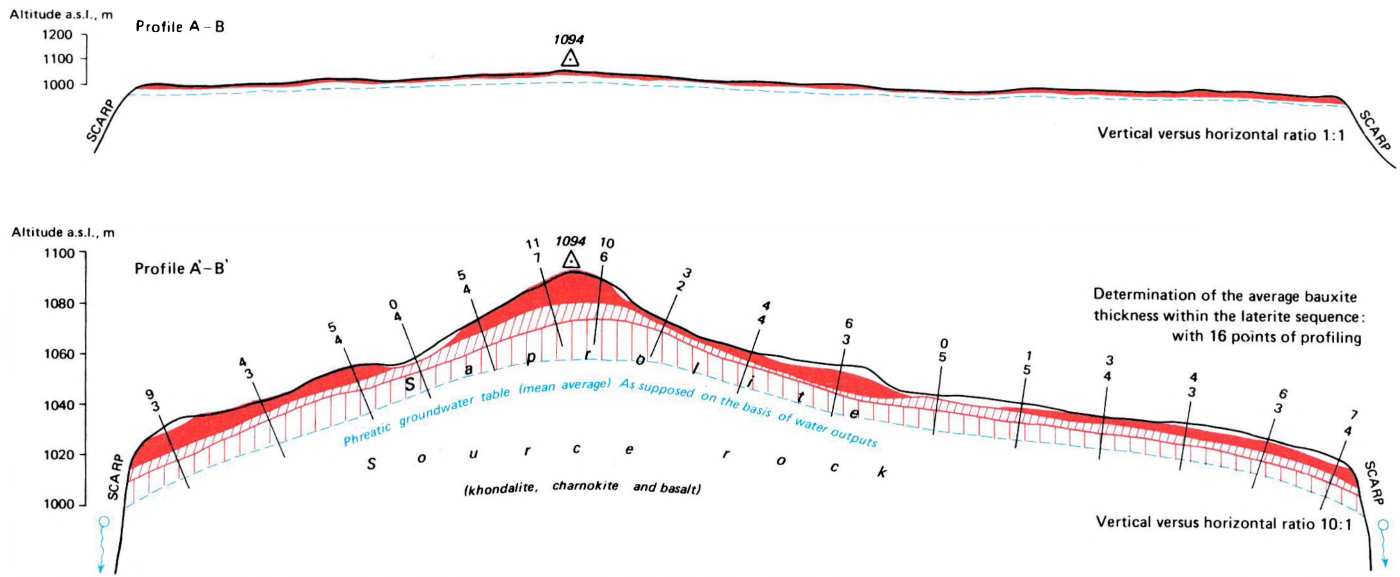


Fig. 68 Schematical geological profiles of the Baphlimali Plateau (Orissa, India)

According to virtual exploration data

Ground area of the plateau: 9.6 km^2
Average bauxite thickness: 1.2 m
Average wet bauxite density: 1.99
Reserves: 195.73 million MT=196 million MT
Difference in the reserves: 196 – 170=–26 million MT=13.3%

According to the assessment of the bauxite potential by the geo-hydromorphological profiling method

Calculation of the average bauxite thickness:

Average thickness of ore with >40% available alumina: $\frac{78}{16}$ = 4.9 metres

Average thickness of one with 30–40% available alumina: $\frac{64}{16}$ = 4.0 metres

Average thickness of estimated commercial ore body: 4.9+4.0= 8.9 metres
Ground area of the plateau=~9–10 km^2. Average wet bauxite density=2.0 MT/m^3
Ore reserves to be expected: ~170 million MT

Example worked out for Baphlimali Plateau (Orissa, India)

[Assessment of the bauxite potential (for calculated and estimated reserves) by the geological and hydro-geomorphological method]

Estimation/calculation of the average ore grade by means of factor equivalents

Starting assumption: bauxite reserves to be expected ~170 million MT

Their explected ore grade:

Calculation of the ore grade by the new method for Al_2O_3:

Source rock: Khondalite, charnokite and basalt

Their distribution in ground area is unknown, for this reason, rations 1/3–1/3–1/3 have been presumed

Mean average of Al_2O_3		Conversion factor equivalent
for basalt	14%	3.3 (2.0–5.6)
for khondalite	15%	3.2 (2.2–4.9)
for charnokite	17%	2.9 (2.2–3.6)
Average:	46:3=15.3%	9.4:3=3.1

Without corrections: 15.3x3.1=47.4%

Average ore grade according to virtual exploration results

	Al_2O_3 %	SiO_2 %
	45.21*	2.19*
Estimated ore grade based on the survey	47.4	4.4
Absolute deviation from the real figure	+2.2	+2.2
Percentage deviation in % of the real figure	(+4.9)	(+100)

Estimation		
for SiO_2 content		for Fe_2 content
49%	9.0	an average of 25–28%
59%	10.2	
62%	7.9	
170:3=56.7%	27.1:3=9.0	Average: 26,5%
56.7:9=6.3%**		

* The deviation calculated for the figure of merit is infinistesimal (–2.2%)

Figure of merit (F_m) = $Al_2O_3 - 2SiO_2$ %

In case of virtual value: 45.21–2(2.19)=40,83%

Using factor equivalent: 47. 4–2(4.4)=38.6%

Deviation =–2.2%

**SiO_2 :6.3% is to be reduced to 4.4% by using the correction of the topo-morphological effects

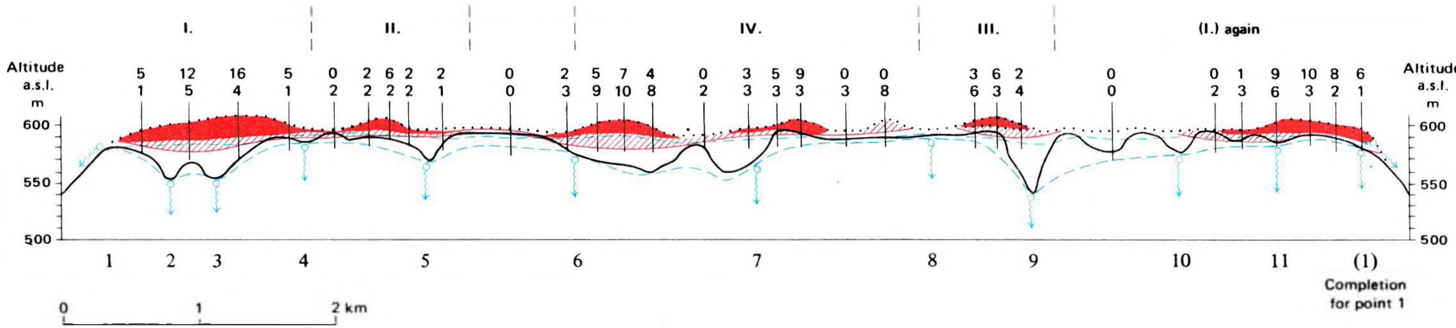


Fig. 69 Circular profile accross water output points 1–11–(1) (Refer to Fig. 65.)

Calculation of average bauxite thickness

Average thickness of Block I

$= \frac{5+12+16+5}{4} = \frac{38}{4} = 9.5$ m

$= \frac{1+5+4+1}{4} = \frac{11}{4} = 2.75$ m

Average thickness of Block II

$= \frac{0+2+6+2+2}{5} = \frac{12}{5} = 2.4$ m

$= \frac{2+2+2+2+1}{5} = \frac{9}{5} = 1.8$ m

Average thickness of Block IV

$= \frac{2+5+7+4+0+3+5+9+0+0}{10} = \frac{35}{10} = 3.5$ m

$= \frac{3+9+10+8+2+3+3+3+3+8}{10} = \frac{52}{10} = 5.2$ m

Average thickness of Block III

$= \frac{3+6+2}{3} = \frac{11}{3} = 3.66$ m

$= \frac{6+3+4}{3} = \frac{13}{3} = 4.33$ m

Potential laterite-bauxite reserves of the plateau

Ground area of block (with bauxite) x average thickness x specific density (wet) = Reserves thousand MT

Block I = 360x9.5 x2.0 = 6.840 thousand MT
450x2.75x2.0 = 2.475 thousand MT
Reserves of the block I = 9.315 thousand MT

Block II = 80x2.4 x2.0 = 384 thousand MT
110x1.8 x2.0 = 396 thousand MT
Reserves of the block II = 780 thousand MT

Determination of the ground area from the aggregate data of circular, longitudinal and transversal sections, re-plotting. Area is determined done by planimetric measurement. (Blocks III. and IV. are to be calculated similarly to Blocks I. and II.)

The calculation of the average ore grade:

Basic information to start with: (in case of proved mother rock)* Al_2O_3 and SiO_2 contents of the source rocks making up the plateau weigthed with their area of occurrence.

Example:			Average
granite	Al_2O_3	10–15%	~12.5%
	SiO_2	66–72%	~69.0%

The *coefficient of conversion* is the multiplier (Al_2O_3) and divoser (SiO_2), respectively, leading from the average composition of the source rock to that of the bauxite derived from the former.

If there are data enough for determining the coefficient of conversion, then this factor will be taken as a base for comparison, if there are not, then the cumulative bulk average inferred from experience will be used to the same end: 3.5 for Al_2O_3 and $\frac{1}{7.5}$ for SiO_2 f.e. in case of granite(s). The author worked out the cumulative bulk average coefficients of Al_2O_3 and SiO_2 for 18 of the most wide-spread source rocks. Limit of tolerance: ±30%.

The resulting margin of average ore grade will thus be:

	Calculated average	Limit of tolerance: 30%
Al_2O_3	44.0	38.0–51.0
SiO_2	7.3	6.1– 8.5

For the case of the example developed by the proposed method, the potential bauxite resources and their ore grade may be given as follows:

Resources: 2 900 000x6x20=34.8 million MT (±30%)

Average ore grade: Al_2O_3=44% (38–51)

SiO_2=7.3% (6.1–8.5).

The calculation of the quality and quantity of the potential resources, as given in the quoted example, refers to Fig. 68.

* When the mother rock or its quality is unknown, a rough general estimate can be taken into account only on the basis of available information from the environment.

3. VALUES, CHARACTERISTICS AND FINAL DATA TO BE DETERMINED (OR THAT MAY BE DETERMINED) DURING THE SURVEY

1 *Potential areas of (relatively) optimal conditions for bauxitization*

Conditions of delineated area

For thickness	For ore grade
At least 50% of the average thickness of the laterite sequence must be bauxite	The average available alumina of the average bauxite thickness must be ⩾35%

There are three subtypes:

1. area that can be sharply, i.e. readily, delineated by morphology,
2. area that can be poorly, vaguely, delineated by morphology,
3. area impossible to delineate by morphology.

2 *Potential area(s) of (relatively) good or moderate conditions for bauxitization*

Conditions of delineated area

For thickness	For ore grade
At least 25% of the average thickness of the laterite sequence must be bauxite	The average available alumina of the average bauxite thickness must be 25–35%

There are three subtypes:

1. area with distinct boundaries,
2. area with rather obscure, blurred boundaries,
3. area impossible to delineate.

3 *Potential area(s) of (relatively) poor conditions for bauxitization*

Conditions of delineated area

For thickness	For ore grade
Less than 25% of the average thickness of the laterite sequence be bauxite	The average available alumina of the average bauxite thickness be (at least) 15–25%

There are three subtypes:

1. area with distinct boundaries,
2. area with rather obscure, blurred boundaries,
3. area impossible to delineate.

4 *Optimization of the layout for locating strategic research and reconnaissance-control boreholes*

1. The optimal areas and sites for locating boreholes and shafts are selected after the areas that proved to be negative in terms of paragraphs 1, 2 and 3 and their subparagraphs had been discarded. Next to follow is a calculation of the cost-reducing effect of drilling savings achieved as compared to exploration by conventional methods.
2. Using the results of strategic and reconnaissance drilling and pit-sinking, carry out corrective and comparative calculations as to the potential resources to be expected (quantity and quality).

5 *Determination of the total identified resources of laterite-bauxite plateau(s) or plateau-complexes for fixed condition cutoffs:*

Conditions for calculation:
average Al_2O_3 ⩾35%, available alumina ⩾15%,
average thickness ⩾1.0 m

6 *Determination of the total recoverable (workable) reserves of laterite-bauxite plateau(s) for fixed condition cutoffs:*

Conditions for calculation:
average Al_2O_3 ⩾35%, available alumina a minimum of 20 or 25%,
average thickness ⩾1.0 m

Allow for the planned losses to exploitation, 8 or 10%. (Naturally, other different cutoffs can also be used, when required.)

7 *Economic geological assessment of the recoverable (workable) reserves in the light of the infrastructure*

(Quantity, quality, possibilities for mining, cost required, removal of overburden, transportation, haulage, etc are to be calculated in terms of material, cost, etc for each country, for particular geological and geographic circumstances and for individual ore bodies separately. Work to be done by experts: geologists–mining engineers–economists.)

1. Theoretical specific productivity index (Pr^t index) determination by plateaus. (As referred to the total expected geological and expected recoverable ore resources.)

Classification:

	Expected (modelled) geological (in million MT/km²)		Expected (modelled) recoverable (in million MT/km²)
7.1.1. Pr^t =	⩾25	very good	(>10)
7.1.2. Pr^t =	15–25	good	(5–10)
7.1.3. Pr^t =	5–15	moderate	(2–5)
7.1.4. Pr^t =	0 practically	barren	0

or there is no commercial bauxite here (but traces of bauxite may exist on these types of plateaus too).

2. Determination of the theoretical workability index (Wi^t). As calculated for groups of plateaus, plateau-complexes or ore bodies of single plateaus with an optimum of ore concentrations for mining, in terms of recoverable bauxite.

Classification:

Wi^t = ⩾10	very good	
Wi^t = 5–10	good	considerable profits
Wi^t = 3– 5	moderate profitable	profitable
Wi^t = 1– 3	poor	poor profits (requires deliberate consideration)
Wi^t = <1	noncommercial	

8 *Compilation of resources reliability maps and assessment system for laterite-bauxite plateaus with ore bodies exploited. (Expressed by ratios)*

For quantity

Calculated potential resources	Reserves evidenced by exploration		Recovered reserves as compared to the potentially recoverable ones	
	reduction %	increase %	reduction %	increase %
1	0.94	1.18	0.79	1.30

For ore grade (in % of average available alumina)

Average available alumina of the calculated potentially recoverable reserves	Available alumina of the recoverable reserves evidenced by exploration		Average available alumina of the recovered reserves as compared to the potentially recoverable ones	
	reduction %	increase %	reduction %	increase %
1	0.79	1.26	0.84	1.20

RENTABILITY EVALUATION OF THE METHOD

ECONOMIC RESULTS TO BE EXPECTED FROM PRACTICAL APPLICATIONS OF THE METHOD

In any tropical-subtropical country with potential resources of plateau- and peneplain-type bauxite already referred to in the preceding chapters, where this forecast method will be adopted and used, considerable progress as compared to earlier results achieved by conventional methods is to be reckoned with.

Progress in this case means first of all *economic achievements,* in the second place a *wide gamut of surplus information* and, as a result of systematization, ***results eligible to processing by scientific methods.***

The main topics the economic achievements that may be expected from the applications of the method can be grouped into are as follows:

- Reliability of delineation and distribution of prospective areas
  - laterally section
  - vertical section
- Reliability of calculation of resources
  - quantity (identified and recoverable)
  - quality
    - Al_2O_3 – (available alumina)
    - SiO_2 – (figure of merit)
    - Fe_2O_3
- Identification of other associated mineral commodities (refractory clay, aluminium-iron ore, nickel-laterite, chromium-laterite, etc)
- Drilling or/and pitting optimization and rentability of exploration
- Industrial developments: optimization

In connection with progress in terms of *surplus information,* the main topics to be dealt with as options for further developments include:

- uniform principles in developing the data input system,
- system of data banking,
- establishment of data banks by countries or, possibly, by regions,
- options for interchange between national data bases,
- options for computerized connection and continuous control between computer-enhanced forecast results and exploration and mining data,
- options for establishing a world data bank (provided that such a development under the auspices of UNO or other international organizations is possible).

Main topics of *scientific research* based on results to be expected:

– Detailed studies aimed at a more profound understanding of lateritization and, in this context, primarily of the genetic factors of laterite-bauxites (Continuation of Project No. 129! Lateritization Processes).

– Criteria and regularities of the formation, distribution, extension and preservation of plateau- and peneplain-type laterite-bauxites, possibilities for typology, systematization, adding precision to well-known classification characteristics, definition of new ones.

– Studies aimed at a more profound understanding of the genetic circumstances of other associated mineral commodities (kaolinite, refractory clay, iron ore, nickel-laterite, etc).

– Studies aimed at a scientific understanding of the Earth's laterite-bauxite zones globally, in general, and in more detail, in particular; production of a wealth of large-scale information for synthesis; finally, carrying out the synthesis by international teamwork.

At present it is till impossible to assess the importance the forecast method may have for the practice, for the diffusion of information and for scientific progress, if adopted and brought on stream. For this reason, all we can do for the moment is to outline some questions concerning the economic results that are observable in direct practice and that are to be expected in the long run: considerations simply based on preliminary calculations.

Delineation of prospective area: reliability of distribution

Tracing the boundaries (laterally). Whenever the method is used in any country, the non-inclusion of an area with potential resources of plateau- or peneplain type in the register of areas meeting the conditions (climatical, morphological, etc) for lateritic bauxitization is out of question. The survey embraces the whole national area with 100% completeness. The locating of prospective areas and their distribution by using the discard-and-select approach based on the availability of the genetic and preservation factors involved is also done with such a high degree of confidence that, in this case too, a 100% fidelity may be reckoned with. This means that the bauxite resources to be identified must be (with a safety factor of about 99%) located within the areas selected for the follow-up. Only some "buried plateau" occurrences unreflected by surface morphology and characterized by particular modes of occurrence and geometry may be exceptions to the rule (e.g. Guyana, Suriname, French Guyana).

The reliability of the *vertical cross-section image* (thickness + ore grade) is guaranteed primarily by the hydro-geomorphological and circle-profile surveying methods (that have very well stood the test of practice) and the empirical factor-equivalents of ore grade calculations applying to different types of source rocks. The accuracy and reliability that can be achieved by these means depend on a number of factors and their interrelations that are impossible to formulate exactly in mathematical terms. Anyway, the trends can be expressed mathematically and, when these are plotted in a system of coordinates, the amplitudes of the possible standard deviations from the axial directions on both sides will, on the average, in no case be more than 30% as compared to the arithmetical mean. In other words, *the highest factor of uncertainty in assessing the ore* *grade is in the case of SiO_2, this one being the most vulnerable component of the whole system.* The trends and variability of Al_2O_3 are less unsteady. As far as the average Fe_2O_3 content is concerned, its values are given, as a complementary main quality parameter, primarily for areas with presumed ore bodies of extreme position, mode of occurrence, geometry, water balance, etc, not always being included in the array of ore grade characteristics. Its response in the profile to water saturation (high position of groundwater table, proximity of sea level etc) and to morphologically deeper positions is particularly marked, but a critical temperature range ($\geqslant 25^\circ$ on the average) and the composition of the source rocks also influence it considerably. To forecast its extreme variations, to locate iron-poor (Fe_2O_3 content $\leqslant 5\%$) and iron-rich (Fe_2O_3 content $\geqslant 35\%$) bauxites and to predict resources and ore grades to be expected is very important, having considerable influence on the mining and ore processing technologies to be adopted and the ore's eligibleness to being processed at all: criteria important to ponder when assessing the rentability of a particular deposit.

Reliability of calculating the reserves

The reliability of calculating the potential laterite-bauxite resources in a particular country by the method here proposed will be the higher, the larger the area, the higher number of the deposits and the greater the amount of the reserves are. The reserves of slope-type laterite bauxites or those of laterite-bauxites occasionally extending from a plateau well onto the slopes are treated as ***additive reserves***, being, in some cases, indicated separately. The calculation of these does not belong to the basic principles of the method. On the basis of analogies, the known exploration-evaluation data can be processed so as to determine specific values relative to selected potential areas and subareas (specific potential of an area = million MT/10 000 km^2 or million MT/250 000 km^2), parameters enabling one to carry out a tentative assessment of the magnitude of the resources to be expected in potential areas not yet surveyed.

E.g. Brazil. Reserves and specific area-potential scalculated for potential area-squares covering explored or just partly explored bauxite areas*

Table 1

Basic square	Deposit	(Map) Surface area million km^2	Reserves million MT	Specific area-potential MT/km^2
B	Trombetas–Nhamunda	0.19	~1.300	~6.800 (6842)
C	Jari–Paru–Amapá–Almeirim	0.23	~ 700	~3.000 (3043)
F	Paragominas–Pará	0.23	~1.100	~4.800 (4783)
N	Ouro Prêto–Diamantina–Langinha	0.25	~ 500	~2.200 (2174)
O	Poços de Caldas–Sorocaba	0.22	~ 400	~1.800 (1818)
P	Barra do Pirai–Rio de Janeiro	0.09	~ 200	~2.200 (2222)
Total B–P	Known major areas of bauxite occurrence in sum total	1.21	~4.200	~3.500 (3478)

* The data included in the above table do not reflect the proved realistic reserves and the latest situation. These represent only approximate data and meaning just to show the method of estimation, nothing else.

If the expected reserves of the squares plotted upon the other potential bauxite areas of Brazil are calculated by means of the average of the above known* major areas combined, then the magnitudes that have been obtained for the total of the expected bauxite reserves of Brazil will be as follows (see Fig. 5):

Table 2

Basic square	Surface area million km^2	Specific area-potential MT/km^2	Potential resources to be expected million MT
A	0.23	3478	~800
D	0.25	3478	~870
E	0.25	3478	~870
G	0.18	3478	~626
H	0.17	3478	~590
I	0.12	3478	~420
J	0.21	3478	~730
K	0.25	3478	~870
L	0 25	3478	~870
M	0.25	3478	~870
Other known major areas with potential resources	2.16	3478	~7.500 (7.514)

As evident from the above schematical preliminary calculation, the potential laterite-bauxite reserves in Brazil, as calculated by using the specific area-potential values of the squares, amount (in terms of order of magnitude) to 7.5 thousand million MT or so. If the known and partly hypothetical resources of about 5 thousand million MT are the minimum to reckon with for the time being, so the total of the bauxite potential of Brazil may be taken to be about 12.5 thousand million MT. This means that the resources that are still to be explored are by a factor of 1.5 more than the present-day figure. In the event, if the method is used, it will be possible, of course, to add a lot of further precision to these data.

Even in the case of the assessment of very little, infinitesimal, reserves with no analogy to rely on is a standard deviation from the really existing reserves (subsequently confirmed by mining results) of more than 50% improbable. And if the average of larger areas and reserves put together is taken, the resulting margin of error will certainly be less than 30%. This is a very good margin, considering that in case of explored, categorized, reserves of bauxite it may be even greater, at least in part. In case of hypothetical and speculative resources, it may be as high as ±80%, in fact, it may occasionally amount to hundreds of %. The afore-mentioned margin of error of ±30%, as an average extreme value, applies to the ore grade as well (Al_2O_3, SiO_2 and Fe_2O_3). In this context, the value of SiO_2 is most unsteady. This means that 30% fidelity applies as a rule to bauxites of moderate SiO_2 content [e.g. in case of an SiO_2 content of 8% (in absolute value),

*These, however, still include a considerable quantity of potential resources that have not yet been taken into account!

the standard deviation may vary between ±2.4 and 2.5%, in other words 8=5.6–10.5]. In case of low SiO_2 values the relative percentage of error may increase to 50, in fact, even to 100%. For example, in case of a ±50% margin, an SiO_2 content of 4% may include SiO_2 values of even 2–6% and, at a 90% margin, the virtual values corresponding to an SiO_2 content of 2% will vary between 0.2 and 3.8%.

The quantitative and qualitative average values of the potential resources determined during the survey, the delineation of the resources laterally and vertically (altitude, position of occurrence, etc), the infrastructure of the environment and the aspects of environmental protection will enable, when put together for comparison, to select deposits suitable for rentable follow-up developments (continued, more detailed exploration, mining design, location and development of mines, etc) and determine the steps to be taken in implementing such projects. In some cases, such an approach may spare a developing country the need for quite considerable investments (which is all the more important as the majority of these countries are very short of funds). On top of that, it will create possibilities for selecting the optimum for industrial developments by relying on a broader gamut of parameters. If there is a possibility for checking the method with the data of already known plateau-type laterite-bauxite deposits explored in detail (reserves and ore grade), the resolution of the method in terms of reliability of resources and ore grade will be considerably improved and, with this experience in hand, the explorers will be able to minimize the local anomalies.

In parallel with the survey, the potential resources of other mineral commodities associated with a similar environment, but different in type (refractory clay, lateritic iron ore, lateritic manganese ore, nickel and chromium ores, etc) (and, in part, their average ore grades, too) may be determined: an option that may locally put forward the idea of complex recovery schemes.

Drilling (pitting) optimization and rentability of exploration

One of the most tangible economic benefits to be drawn from the whole complex forecast method consists in that, by selecting the prospective areas of occurrence of high-grade bauxite, it will locate, at the same time, the sites most worthy of putting down a borehole into and that the results of this drilling (or pitting), once performed, will give thickness and ore grade data for a checking up of critical places. Such an optimization of borehole (pit) location will not only provide the method with the possibility of checking itself, but it enable the bauxite explorers to achieve considerable savings in follow-up drilling (pitting) once the check-bore drilling (pitting) has given favourable results. (To refrain from follow-up drilling, of course, is not compulsory, but it is desirable.) At any rate, all in all, the resolution of the method to reckon with is quite encouraging: the number of boreholes (pits) needed for the design and implementation of mining developments (the opening of mines), as compared to conventional exploration needs (the margin of errors in terms of ore grade allowed for being taken equal), will be reduced from one fifth to one tenth. This implies, in itself, considerable savings in research, exploration, material and funds (Fig. 70).

Let us take a rough calculation example:

There is a plateau-complex of 20 km^2 area. To explore it by conventional methods would need to put down, in a grid of 50x50 m or so, a total of about 20x400=8000

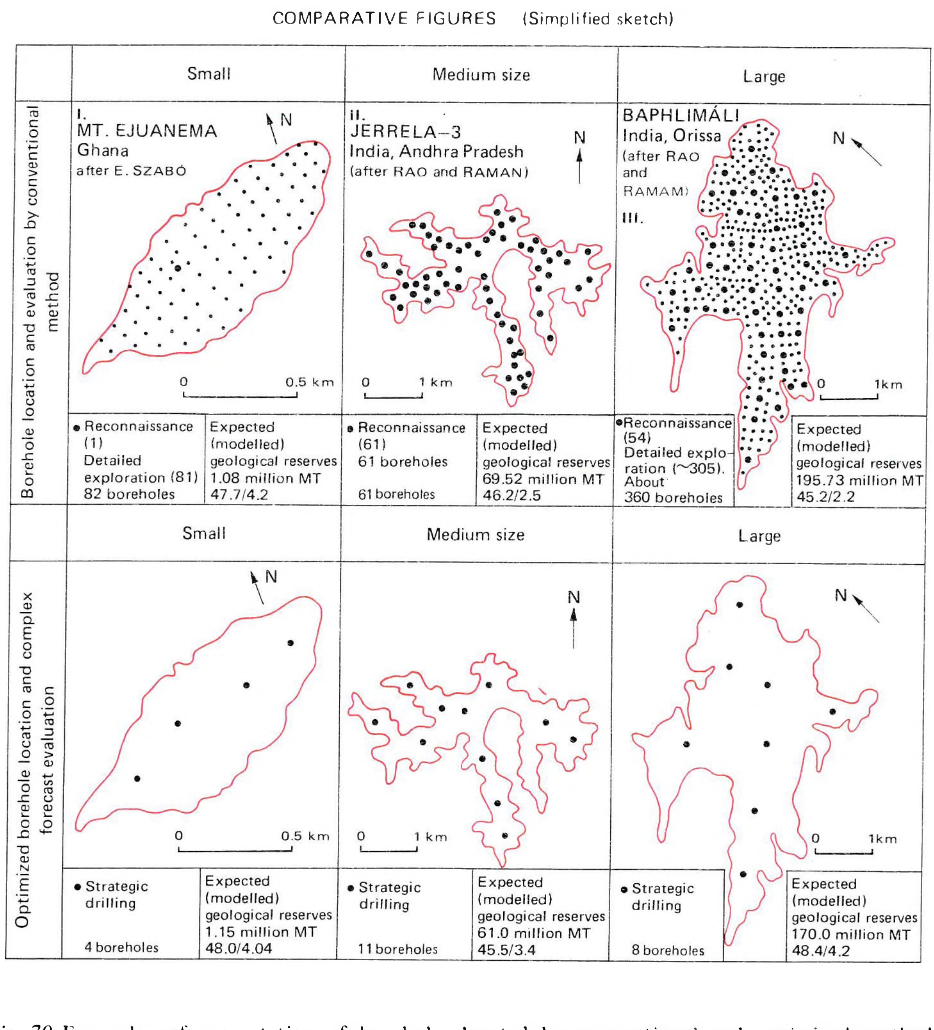


Fig. 70 Examples of presentation of boreholes located by conventional and optimized methods, respectively, and of the results of their assessment (for the quantity of the reserves and their ore grade) in case of single bauxite deposits of small, medium and great size

boreholes with an average depth of 20 m up to completion of the detailed phase of exploration. By using the new complex method, one will be able to reduce the number of boreholes to be put down in optimum-points to as low as 76 (of which 58 will have come up to the expectations). Further borehole concentration will be advisable to carry out in places, where justified by changes in ore grade. These boreholes (a total of 18) will require to put down additional boreholes at points in their neighbourhood in harmony with the planned borehole concentration. Thus the number of additional boreholes will be a maximum of 18x4=72. Of these, 66 will have come up to the modified expectations, 6 will not. The neighbourhoods of these will require the putting down of a maximum of 6x4=24 new boreholes. Of these only 2 will deviate from the forecast. This will add 2x4=8 new boreholes, and so forth and so forth. An addition of the totality of the check-boreholes put down according to the same principles will in every case give a figure that is substantially lower compared to the number of boreholes drilled in a systematic grid.

The difference in this case is essential: instead of 8000 boreholes, only 76+72+24+8=180 boreholes will have to be put down with similar or identical confidence. Consequently, the savings thus achievable will include 8000–180=7820 boreholes, i.e. a total of 7820x20 m=156 400 m of exploratory drilling metrage. Compared with the total number of boreholes that ought to be put down by conventional methods in a conventional grid, this figure will be as low as only 2.3%! In other words, the remaining boreholes, 97.7%, will be allowed to be spared completely! On the other hand, in case of exploration of very small areas, however, the margin is not so good anymore, but, even in this case, a total of about 50% of the boreholes are eligible to be spared!

Now take the example of a preliminary calculation of the cost involved! The size of the savings thus achievable will be as follows:

Prime cost of 1 m of exploratory drilling (wages, equipment, installation, material, public dues, etc, in a developing country, in a desolate region)	USD	4.–
8000 boreholesx20=160 000 m will cost a total of	USD	640 000.–
Total savings in sparing the drilling of a total metrage of 156 400	USD	625 600.–
Cost of computer-enhanced assessment (personal computer+crew salaries of 2 persons for about 3 months+mobile home, etc equipment)	USD	25 600.–
Virtual savings	USD	~600 000.–

If the calculations are made in terms of MT of ore reserves rather than in terms of drilling metrage, then the average amount of explored bauxite reserves corresponding to a total savings of about USD 0.1–0.6 million will be of the order of magnitude of 100 million MT. In case of Brazil, with her calculated potential bauxite reserves of 7.5 thousand million MT (still to be assessed and explored), the savings achievable will be roughly of the order of magnitude as follows:

7.5 thousand million=75x100 million MT
0.1= 7.5, i.e. from USD 7 500 000.–
75x0.6=45.0, i.e. to USD 45 000 000.–

When extended to cover the potential laterite-bauxite resources of the Earth, i.e. in case of a survey, the largest possible of its kind both in principle and in practice, the calculation will give a total of 25–30 thousand million MT of potential laterite-bauxite resources, which, when converted into savings, may result in 250–300x0,6=150–180 million USD. In other words, the total savings thus achievable, merely in terms of exploratory drilling spared, will be at the average present-day price level (1987), of the order of 150 000 000–180 000 000 US dollars. The above savings in drilling and cost do not mean that the information that can be drawn from 1/10 of the number of boreholes claimed by the conventional method will be sufficient for carrying out the tasks emerging in the mining development and exploitation phase. Naturally, in dependence on the variability of the ore grade of the bauxite (this may vary from one deposit to the other), in the mining development phase, operational boreholes or pits will have to be drilled or sunk, respectively, or channel samples will have to be collected from the faces of the workings. The analyses of these samples will provide contributory information and safety as to the quality of the ore to be extracted and, consequently, as to the layout of the mining operations to be performed. Occasional local anomalies of ore grade heavily deviating from the neighbourhoods of the boreholes (pits) that have been located according to the optimization schemes will still correspond to a deviation of the same order of magnitude as the deviations observable in deposits explored with a much more closely spaced grid. This peculiarity is due to the frequent changes in ore grade (varying practically at 10 cm intervals) already referred to.

What may be added to the benefits that have been drawn from this preliminary estimate are the economic results, i.e. in situ value, of the plateau- and peneplain-type laterite-bauxites which were formerly just supposed to be present in traces, but which have been "reconnoitred" by the forecast method and which are hoped to turn out to be a reality, when corroborated by the follow-up. Let us restrict ourselves to the reserves that will probably be exploitable on medium or long term and that seem to be favourable from the viewpoint of *industrial developments,* settlement planning, infrastructure, ore grade and ore reserves alike. The volume of such resources varies largely from one country to the other, the total supposed for all the countries that may come into account being a very cautiously estimated minimum of 2 thousand million MT or so (reckoning with development possibilities up to the year 2000 or so). If the in situ value of one MT of such type of bauxite is taken (at the price level of 1988) to be a minimum of USD 15.–, then the average in situ value of the totality of the bauxite reserves discovered and to be reckoned with as eligible for mining, etc developments will be equivalent to 2 000 000 000x15=30 000 000 000, i.e. to 30 thousand million US dollars.

The advantage of the method in this case consists in the first place in providing a possibility for the economically rentable inclusion in medium- to long-term plans or programmes of such a magnitude of primary aluminium-carrying industrial raw material (bauxite) and specifying their distribution in terms of geographic extension and ore grade dispersion. The prospects thus achievable may substantially improve and speed up the circumstances of the creation and/or improvement and extension of the aluminium industry in some developing countries. The knowledge of the potentialities existing on an even wider scale may contribute to an optimization of the industrial development throughout the Globe, in general, and in each interested country, in particular.

APPENDIX

CALCULATION VARIANTS OF POTENTIAL BAUXITE DEPOSITS (PLATEAU-TYPE) IN CASE OF DIFFERENT LEVELS OF INFORMATION

Variant I

Raw estimation

For quantity: Estimated (in case of large plateaus: measured) ground area in square kilometres multiplied by 5 metres of average (global average) laterite-bauxite thickness, multiplied, in turn, by an average wet volume density of 1.7. Reserves in metric tons or in million of MT.

For quality: Start from the average Al_2O_3 and SiO_2 content of the globally known source rocks, as inferred from geological maps or supposed; calculate the average ore grade of the bauxite presumably generated from it and take the respective factor equivalents into consideration.

Consult a map on a scale of 1:100 000 or larger on which only the sketchy contour of the plateau is available. The source rock is known only as inferred from a sketchy geological map, no analyses being available. No trace of laterite-bauxite is known, no topo-morphological data are available, the climatic data being known only as inferred from global data. There is no surveyed laterite-bauxite plateau in the surroundings; there are no known data regarding laterite-bauxite. (Insufficient and low information level.)

Variant II

Approximate estimation

For quantity: Area to be measured from the map in sq.kms. The laterite-bauxite thickness can be determined analogically from the measured data of the surrounding laterite-bauxite. The volume density (wet, average) can be established by analogy. Resources in millions of MT.

For quality: The source rock is known as inferred from the geological map and by analogies with rocks in adjacent areas. The same holds true of the Al_2O_3 and SiO_2 content to be determined subsequently. Factor equivalents can be established by analogies with the ore grades of surrounding bauxites.

The data are to be taken down and measured from topographical map(s) having a scale of 1:50 000–1:100 000 with at least 25 m contour lines. The drainage pattern can be determined sufficiently. There are traces of laterite-bauxite in the neighbourhood; the data can be surveyed or perhaps obtained at the level of preliminary research. The data involved include global data on climatic conditions and topo-morphology, but sometimes also nearby or local observations or data obtained by analogies. (Medium information level.)

Variant III

Founded estimation

For quantity: Area to be measured from the map in sq.kms. The bauxite thickness can be established from distorted vertical sections and circular profiling. The average wet volume density is similarly based on data measured in the surroundings. Resources in millions of metric tons.

For quality: The source rock is exactly known, its average Al_2O_3 and SiO_2 contents as well as the Al_2O_3 and SiO_2 of the bauxite generated from the source rock are known analogically from exploration and mining results. The factor equivalents can be inferred from the fixed data of the factors.

The data are to be taken down and measured from topographic map(s) having a scale of 1:25 000–1:50 000 with at least 10 m contour lines. The water-balance map is sufficient for establishing the water-balance of the plateaus by vertical distortion sectioning and circular sectioning techniques and by marking off sub-plateaus and section segments with bauxite content. From measurements taken in different points, both the average ore thickness and, in some parts, the extent of the bauxite spots can be determined.

Several plateaus with laterite-bauxite are known to occur in the surroundings, partly from exploration results and/or partly from the mining record. There is a possibility of taking down correlation diagrams analogically as well as establishing correlations, trends, to be taken into consideration when assessing the ore grade. For creation of factor equivalents, there are partly measured, partly calculated data on climatic conditions, morphology, etc. (Good information level.)

Variant IV

Determination of corrected potential resources or reserves.

For quantity: Plateaus are measured from the map in sq. kms, the corrected extension of the bauxite in sq. kms, its corrected average thickness in m.

The average wet volume density can be partly inferred in an analogical way, partly established by direct measurements. Resources or reserves in millions of MT.

For quality. Average quality: Average Al_2O_3 and SiO_2 content calculated with correlation diagrams and factor equivalents for bauxite, corrected with data other than average from boreholes (or pits) drilled in selected points.

There is a topographical map on a scale of 1:10 000–1:25 000 based on detailed local survey, with at least 2,5 m contour-line spacing. From the map, all the necessary data can be inferred (tilting angle, plateau-morphology, marshy parts, sites of water outputs for water-balance measurements, etc). The water-balance of the plateau(s), the average thickness of bauxite, its geological features and the extension of aquifers can be determined from vertically magnified and circular sections. Several plateaus with laterite-bauxite are known to occur in the surroundings and the data necessary for analogy and for taking down correlation diagrams are at disposal.

Orientation boreholes (pits) have been sunk at appointed locations of the surveyed plateau and thus the potential calculated resources (or reserves) (quantity and ore grade) can be assessed more exactly by relying on the results available. Concrete measurements and analyses of the source rock and the bauxite are available from several points of the plateau. (Very good information level.)

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